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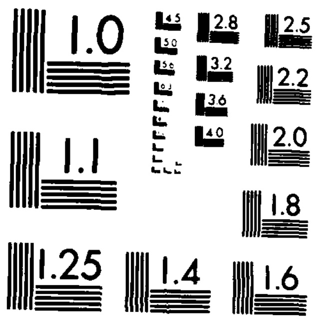

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DEPARTMENT OF DEFENCE

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MECHANICAL ENGINEERING REPORT 162

ON SEPARATING TURBULENT BOUNDARY LAYERS

by

W. H. Schofield

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ON SEPARATING TURBULENT BOUNDARY LAYERS

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W. H. Schofield

SUMMARY

Some data and theories of two dimensional turbulent boundary layer separation are considered. A description of separating layers based on the Schofield and Perry similarity is proposed. It is shown that the Schofield and Perry defect law can describe detached profiles as accurately as it can describe attached profiles if the origin is shifted, from the wall, out to the zero velocity position in the detached flow. For attached flow the inner wall matching condition is the usual law of the wall. For detached flow the wall matching condition is provided by the reversed flow for which a modified similarity scale is proposed. This extended validity of the Schofield and Perry defect law implies a unique progression of mean velocity profile shapes up to and through separation. Good experimental support for this theoretical result is presented. Experimental evidence also supports the proposition that detachment (and perhaps reattachment) always occurs at the same position on the locus of profile shapes, that is, boundary layers detach with a universal mean profile shape. A comparison of this result with other separation theories leads to another conclusion: that layers which separate in moving equilibrium not only detach with the same mean profile shape, but detach at the same local pressure gradient.

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CONTENTS

NOTATION

A	constant in logarithmic law of the wall
B	integral layer thickness in Schofield and Perry theory
B_D	integral thickness B with origin for y at $u = 0$ in the detached flow
C	constant
c_f'	skin friction coefficient $(= \tau_0/\frac{1}{2}\rho U_1^2)$
c_f	time averaged value of c_f'
D	depth of back flow
H	form factor $(= \delta^*/\theta)$
H_D	form factor with origin for y at $u = 0$ in the detached flow
L	distance from the wall to τ_m
m	pressure gradient index
u	mean flow velocity in x direction
u_τ	friction velocity $(= \sqrt{\tau_0/\rho})$
U_m	velocity scale $(= \sqrt{\tau_m/\rho})$
U_s	velocity scale for Schofield and Perry defect law
U_1	free stream velocity
x	distance downstream
y	distance from wall
y_c	distance from wall to logarithmic–half power law junction point
y_D	distance from the $u = 0$ streamline in detached flow
γ_p	fraction of time that flow near the wall spends in flowing upstream
δ	boundary layer total thickness
δ_c	Coles' total layer thickness
δ^*	displacement thickness $= \int_0^\delta (1 - u/U_1)dy$
δ_D^*	$\int_{y_D}^\delta (1 - u/U_1)dy$
θ	momentum thickness
κ	Karman's constant
ν	kinematic viscosity of fluid
Π	Coles' wake strength parameter
ρ	density of fluid

τ_o	wall shear stress
τ_m	maximum shear stress
ω	Coles' wake function

1. INTRODUCTION

Since boundary layer separation is usually responsible for setting an upper limit to the performance of aerodynamic devices, a major aim of fluid mechanics research is to describe and predict separating boundary layers. The subsequent problem of developing an ability to describe separated boundary layer flow is less pressing but is of considerable practical interest in off-design performance and transistory flow behaviour of aerodynamic components. As the majority of separating layers are turbulent, this is the case that attracts most research interest.

Although the topic is an old one, there has been limited progress in analytical work and the experimental data that has existed until recently was sparse and of relatively poor quality. An important first step towards progress in this field has recently been taken by Simpson *et al.* (1978, 1981) who have produced two sets of high quality measurements of separating and separated flows. The next two important steps are: to find simple, universal, similarity relationships that accurately describe both separating and separated flow, and if possible devise a simple universal separation criterion. These two problems are the subject of new proposals presented in this report. They could form the basis of the final step, that of devising a simple calculation method to predict both separating and separated flow.

2. SIMILARITY RELATIONS

2.1 Attached Flow

We start, as other writers have, by considering similarity relations that give useful descriptions of non-separating flows, to see if they can be applied (with or without adaption), to separating flow.

The best established similarity relation is the logarithmic law of the wall (see Coles (1968)) which is valid in most turbulent wall layers. Stratford (1959) has claimed that it failed in layers held at 'incipient separation.' While it is well established that the logarithmic region decreases in vertical extent (from the wall) as separation is approached, Coles and Hirst (1960) showed that the majority of Stratford's near separating layers had, in fact, small logarithmic regions. This conclusion was supported by Simpson *et al.* (1977, 1980) who showed that the logarithmic region was valid in separating layers up to the location where the wall flow contains instantaneous flow reversals. This validity also apparently extends to reattaching profiles as shown by some recent results (figure 1) of Schofield (1983) who measured mean velocity profiles through a separation bubble caused by a normal shock wave interacting with a turbulent boundary layer. Hence this law is very robust, but is limited in that it describes only a small portion of a separating or reattaching layer.

It can be extended to cover the whole layer by adding on Coles' wake function (Coles 1956), viz.

$$\frac{u}{u_\tau} = \frac{1}{\kappa}\log_e\frac{yu_\tau}{\nu} + A + \frac{\Pi}{\kappa}\omega(y/\delta_c) \qquad (1)$$

This description has several defects. Firstly the profile description is not universal at the outer edge of the layer (see Perry and Joubert (1963)). Secondly at separation and reattachment, it predicts that the logarithmic law has disappeared and the profile is a pure (Coles) wake. Experimental results (Seddon 1967), Schofield (1983)) do not support such a profile shape at separation or reattachment. Finally the description involves three independent parameters (u_τ, Π, δ_c) which makes it difficult to use as a prediction tool compared with a two parameter model.

Two parameter descriptions of a boundary layer mean velocity profile employ a length scale and a velocity scale. Traditionally these scales have been the wall shear velocity u_τ and a total layer thickness. A layer in adverse pressure gradient flow that could be described in terms of these two local variables alone was termed an equilibrium layer by Clauser (1954). Later authors introduced the concept of 'moving equilibrium', in which the external forces on a layer varied slowly with distance and the layer moved smoothly through a range of equilibrium states, continuously adjusting to them so that the profile could at all times be described in terms of two local parameters alone. This concept is widely used in calculation methods for the prediction of turbulent boundary layer development in adverse pressure gradients.

For boundary layers near separation the approach outlined above encounters severe difficulties associated with the fact that as the boundary layer approaches separation the wall shearing stress approaches zero and with it, the velocity scale u_τ. For this reason workers in the field Mellor and Gibson (1966), Townsend (1960, 1961, 1976), Kadar and Yaglom (1978) and Yaglom 1979)) have abandoned u_τ as a scale for flows near separation and replaced it with one based on pressure gradient. The scales selected have been recently criticized by Schofield (1981) on both practical and theoretical grounds. However even if reasonable descriptions of layers approaching separation are possible using these velocity scales, they do not show any promise of being able to describe flow that has detached.

Schofield and Perry (1972) suggested that the appropriate velocity scale for boundary layers in adverse pressure gradient flow was U_m, related to the maximum shear stress in the layer ($U_m = \sqrt{\tau_m/\rho}$), rather than the wall shear stress ($u_\tau = \sqrt{\tau_0/\rho}$). The similarity relations based on this scale have been shown to give good descriptions of mean profiles in moderate to strong adverse pressure gradient layers. As they are to be adapted in this report to describe separating, separated and reattaching profiles the equations and their relationships will be outlined.[1]

In an adverse pressure gradient turbulent boundary layer in which the maximum shear stress is more important to flow development than the wall shear (formally $\tau_m/\tau_0 \geqslant 3/2$), the outer 90% of the mean velocity profile is accurately described by

$$\frac{U_1-u}{U_s} = 1-0\cdot4(y/B)^{1/2}-0\cdot6\sin\left(\frac{\pi y}{2B}\right) \tag{2}$$

where

$$U_s = 8\cdot0\,(B/L)^{1/2}\,U_m \tag{3}$$

and

$$B = 2\cdot86\,\delta^*\,(U_1/U_s). \tag{4}$$

Near the wall, equation 2 can be expressed in the half power from

$$\frac{u}{U_1} = 0\cdot47\left(\frac{U_s}{U_1}\right)^{3/2}\left(\frac{y}{\delta^*}\right)^{1/2}+1-\frac{U_s}{U_1}. \tag{5}$$

Equation 5 is used to determine the velocity ratio U_s/U_1 (see Perry and Schofield (1973)) in the same way that Clauser (1954) determined u_τ/U_1 from the logarithmic law of the wall. Examples of this similarity are given in figures 2 and 3 using the results of Schofield (1983). In figure 2 the velocity ratios are determined using equation 5; figure 2a shows the attached profiles from a boundary layer that was locally separated by a normal shock wave and then subsequently developed in an adverse pressure gradient; figure 2b shows attached profiles from a boundary layer that develops in an adverse pressure gradient alone. The velocity ratios determined from the (good) agreement between experiment and theoretical lines shown in figure 2 are used with equations 2 and 4 to describe the whole mean profile. The comparisons of experiment and theory shown in figure 3 are in general good[2] and are typical of previous results (see Simpson *et al.* (1977, 1980), Samuel (1973), Perry and Fairlie (1975), Schofield (1981), Schofield and Perry (1972)). The lack of correlation near the wall ($y/B < 0\cdot1$) is to be expected as the Perry and Schofield defect law is not valid in the law of the wall region.

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1. For full details see Schofield and Perry (1972), Perry and Schofield (1973) and Schofield (1981).

2. Two profiles immediately downstream of reattachment in figure 3a (at $x = 0\cdot288$ mm, $x = 0\cdot314$ m) unaccountably do not show the same high degree of correlation that is the norm for adverse pressure gradient layers.

2.2 Detached Flow

As the velocity scale used in Schofield and Perry similarity is related to the maximum shear stress which does not disappear or reverse its direction during flow detachment there seems no theoretical reason why Schofield and Perry similarity should not describe detached flow. The back flow underneath a detached flow is probably strongly influenced by downstream conditions and is unlikely to scale with local outer flow variables, U_s and B. The backflow would form the wall matching condition, taking the place of the usual law of the wall in attached flow.

To test these ideas, the results of Schofield (1983) were analysed. As Schofield's layer was locally separated by a normal shock wave before developing in a strong adverse pressure gradient the data contains separating and reattaching profiles. As only the forward flowing portion of a detached layer could possibly be described by the Schofield and Perry similarity, a new ordinate (y_D) was used which had its origin at $u = 0$ in the detached flow rather than at the wall. Figure 4 shows that the detached mean profiles display half power distributions consistent with equation 5. The correlations are little different from those of the attached profiles in the same layer (see figure 2). Using the values of U_s/U_1 determined in figure 4, the mean detached profiles for $u > 0$ are well described by Schofield and Perry similarity as shown in figure 5. The descriptions are somewhat inaccurate for $0 < y_D/B_D < 0 \cdot 1$ but this is the region where the outer flow is matching itself to the reversed wall flow; it is also the region where deviation from equation 2 is frequently observed in attached flow. Values of the velocity scale are plotted for the entire layer, both attached and detached, in figure 6 and form a fairly smooth continuous curve. The diverse range of profiles in this layer that are described by the Schofield and Perry similarity law are illustrated in figure 7, which emphasises the changes in wall matching condition that apply along the layer.

This evidence suggests that the outer flow maintains its similarity irrespective of what is happening underneath it at the wall and that separation, far from destroying or altering outer similarity, just provides a different wall matching condition for it. If this extension to the range of validity of the Schofield and Perry similarity can be established it would be significant and potentially useful in developing calculation methods for separated boundary layers. Consequently the similarity relations were tested against other separated flow data.

In Simpson's two experiments (Simpson *et al.* (1977), (1981)), velocities were measured in a detached flow with a laser doppler anemometer, as well as with hot wires, hot films and pitot tubes. The resulting data are the most reliable available of a detached flow. Figures 8 and 9 show Simpson's detached profiles (for $y_D/B_D > 0$) on half power co-ordinates. They display half power distributions similar to those shown in Schofield's data (figure 4). Figures 10 and 11 show that these profiles correlate well with the Schofield and Perry similarity relation except in several cases for the range $0 < y_D/B_D < 0 \cdot 1$. These deviations, though perhaps larger than those shown in figure 5, are no larger than deviations that can be found in the corresponding portion of some attached profiles. Thus these profiles are not different in this respect from attached profiles. Further experimental support is given by the two separated bubble flows of Seddon (figures 12, 13, 14 and 15) and the flow of Fairlie[1] (figures 16 and 17).

We have moved then towards a fairly unified description of separating flow. Upstream of detachment, Schofield and Perry similarity accurately describes the outer 90-95% of the flow with the inner wall matching flow being accurately described by the law of the wall. After detachment the forward flowing portion of the flow ($u > 0$) can be described by the Schofield and Perry relations. To complete the description we require a similarity relation for the back flow region ($u < 0$).

2.3 Reversed Flow

It can be argued that reversed flow could be determined by a number of factors, which makes it difficult to formulate simple similarity scales. Firstly the back flow could be considered a wall

1. Fairlie's detached profiles (see Perry and Fairlie (1975)) were measured with a hot wire anemometer system and showed large discontinuous changes of mean velocity across the $u = 0$ position. Similar results were obtained by Simpson *et al.* (1977) with a hot film and these were rejected by the authors as inaccurate compared with the laser doppler measurements. Consequently for this work Fairlie's profiles have been smoothed in the $u = 0$ region.

flow with scales u_τ, ν/u_τ. Simpson *et al.* (1981) showed that these scales could not correlate their data; they also tried unsuccessfully several wall-wake correlation schemes involving the outer flow variables U_1, δ. As the outer flow has been shown here to scale with U_s and B_D, these were tried on a range of back flow data but they also gave hopeless results.

Schofield (1983) showed that the size of the separation bubble in a boundary layer under a shock wave was greatly affected by downstream conditions. Simpson *et al.* (1977, 1981) found that downstream conditions affected the level of backflow in separated regions that did not reattach. It seems therefore that the backflow is a complex region in which both wall and outer flow variables may be important, but one in which the details of downstream constraints on the backflow will be important as well. The resulting flow appears to scale on its own (local) variables. Simpson *et al.* (1981) proposed the maximum backflow velocity (U_N) and its distance from the wall as the two scales, and these gave a fair correlation of his data. It would seem, however, that the distance from the wall to the maximum backflow velocity is a length scale more related to the wall region than to the backflow as a whole. Consequently it is proposed here that a better length scale is the total backflow thickness (D).[1] This is born out by the correlation of Simpson's results in figure 18 which is an improvement on the Simpson *et al.* (1981) correlation. The correlation is not as good for the balance of the backflow data (figure 19). This larger scatter may be explained by the fact that all this data was measured with pitot tubes which are more inaccurate in reversed flow situations than laser doppler anemometers. However, it is pleasing that fair correlation extends someway past the backflow region (i.e. $y > D$), which means that the combination of this backflow similarity with the Schofield and Perry similarity can give a fairly accurate description of the entire detached profile.

3. SEPARATION RELATIONS

3.1 Defect Profile Relations

If any family of mean velocity profiles can be described with a similarity relation of the velocity defect type,

$$\frac{U_1-u}{U_s} = f(y/B) \tag{6}$$

then it can be shown (Clauser (1956), Perry and Fairlie (1975)) that

$$H = \frac{1}{1-C(U_s/U_1)} \tag{7}$$

where C is a constant. In zero pressure gradient flow the velocity defect law has u_τ/U_1 as the velocity scale instead of U_s/U_1. For this case Clauser (1956) determined that

$$H = \frac{1}{1-6\cdot 8\, u_\tau/U_1}$$

and showed that it correlated with a range of zero pressure gradient data on both rough and smooth walls over a wide range of Reynolds number.

For layers in moderate to strong adverse pressure gradients the profiles are described by equation (2) which is in the form of equation (6). In this case the expression for the form factor is

$$H = \frac{1}{1-0\cdot 58\, U_s/U_1}. \tag{8}$$

Fairlie (1973) derived this equation and compared it with a range of data for attached layers. The correlation was reasonable but, as expected, was less than perfect because equation (2) gives poor profile descriptions near the wall (in the wall matching region) whereas the derivation of equation (8) assumes it to be valid right down to the wall.

1. An additional practical point in favour of the total backflow thickness is that the maxima in the backflow velocity profiles tend to be rather flat (see figures 18 and 19) so that the value for the distance to the maximum velocity is difficult to determine accurately.

If we use H_D, the form factor for positive y_D, then the work of the previous section allows

$$H, H_D = \frac{1}{1-0\cdot 58(U_s/U_1)} \tag{9}$$

to apply to all adverse pressure gradient flow, separated as well as attached. As with attached flow this relation will not give a perfect correlation of detached data because equation (2) can give poor profile descriptions for $0 < y_D/B_D < 0\cdot 1$ (see figures 5, 10, 11, 14, 15, 17).

Equation (9) implies that there is a unique H, H_D versus U_s/U_1 locus for attached and separated boundary layers in adverse pressure gradients and that somewhere along this locus separation occurs. Logically if the layers obey Schofield and Perry similarity they must fall on the locus given by equation (9) and figure 20 shows that a wide range of data[1] does correlate satisfactorily with it. In the figure equation (9) is represented by a pair of lines reflecting the equation's imperfect description of profiles near y and $y_D = 0$. Although separating layers follow this locus it does not necessarily follow that detachment occurs for all layers at the same position on the locus, i.e. at a certain value of U_s/U_1.

3.2 Separation Criteria

The traditional condition used to indicate boundary layer detachment is $c_f' = 0$. It is however a rather unsatisfactory criterion because c_f' becomes very small as detachment is approached, decreasing slowly with distance. Thus near detachment c_f' is difficult to measure experimentally and requires a very accurate calculation method to predict the separation position with any accuracy. An approach that avoids these difficulties has been to propose, as a criterion, that there is a universal mean velocity profile shape at detachment. Coles (1956) made such a proposal. He predicted that at detachment (and reattachment) the mean velocity profile reduced to a pure (Coles) wake. As noted previously, experimental results do not support this hypothesis. Sandborn and Kline (1961) also proposed a universal mean velocity profile for detachment that was essentially a curve fit to a collection of separating profiles previously reported in the literature. Unfortunately these studies (all published before 1960) used different definitions of separation and different methods to detect and label detachment, which makes the synthesized criterion by Sandhorn and Kline an unknown mixture of various criteria.

The problem with all these separation criteria is that they use a single value of a time averaged parameter to describe separation which is essentially an intermittent process that develops over a considerable distance. At a recent colloquium on turbulent flow separation (Simpson (1981)) definitions of two dimensional detachment states were agreed on. The definitions were made in terms of the percentage of time that flow near the wall spent in backflow. They are: incipient detachment (ID) which is the condition of 1% backflow ($\gamma_P = 0\cdot 99$) near the wall, intermittent transitory detachment (ITD) with 20% backflow ($\gamma_P = 0\cdot 80$) and transitory detachment (TD) with 50% backflow ($\gamma_P = 0\cdot 5$). Detachment was defined as $c_f' = 0$ and would be very close to the transitory detachment position unless the magnitude of the wall stress near detachment differed markedly during the upstream and downstream flow phases which seems most unlikely. These definitions are appealing as they are precise and employ a measure of flow reversal (γ_P) which reflects the unsteady nature of separation from a surface of small curvature, and it would be convenient to be able to dispense with other concepts of separation and standardise on them. However there are obvious difficulties in doing so. From an experimental point of view γ_P requires sophisticated instrumentation. From a prediction point of view, present calculation methods could not hope to accurately predict γ_P, whereas their ability to predict mean flow parameters is relatively good and rapidly improving. For these reasons we are forced back for the time being into using mean flow parameters. However it does seem possible that γ_P may be uniquely and universally related to the mean flow profile shape and therefore a universal detachment criterion based on Schofield and Perry similarity may be possible.

Figure 21 shows Simpson's flow reversal measurements and the corresponding (Schofield and Perry) velocity scale ratios plotted as functions of downstream distance (x). If the relationship between γ_P and U_s/U_1 shown in this figure applied to all boundary layers then the stages

1. The data is not identified in this diagram but consists of all the data analysed in the course of this work and shown individually in figures 22 and 34.

of separation (incipient detachment, intermittent transitory detachment, transitory detachment) would always occur at the same value of U_s/U_1 and therefore at the same values of H. However only the separating data of Simpson contain intermittency measurements and therefore the values of U_s/U_1 for $\gamma_P = 0{\cdot}01$, $0{\cdot}2$ and $0{\cdot}5$ suggested by figure 21 cannot be tested against other data to see if they are universal. It is possible however to make some test of the (most important) transitory detachment condition through the concomitant detachment criterion of $c_f' = 0$.

Figure 22 shows Simpson *et al.* (1981) data plotted on H, H_D versus U_S/U_1 co-ordinates with ID, ITD and TD marked as lines of constant U_S/U_1; the values of U_S/U_1 for each determined from figure 21. Also shown is the corresponding skin friction distribution which is very near zero at the position of transitory detachment as expected. Profiles with velocity ratios greater than the value at transitory detachment all had negative mean velocities near the wall, i.e. they were detached. Other separating boundary layers give results similar to these and generally support the proposition that boundary layers detach with a velocity ratio near $1{\cdot}18$. Data for five separating layers are presented in figures 23 to 27 and show:

(i) skin friction distributions which can be plausibly extrapolated or (interpolated) to zero at or near the velocity ratio at which Simpson's layer reached transitory detachment,

(ii) that detached[1] mean velocity profiles first appear on the locus of the layer with velocity ratios at or near the value for Simpson's transitory detachment. On the locus of the three layers that reattach after a local separation (figures 23, 24 and 26), the reattaching profiles also first appear with velocity ratios near $1{\cdot}2$.

The experimental support for the proposed detachment criterion ($U_S/U_1 = 1{\cdot}18$) is not perfect. In particular the first detached profiles appear on the locii with velocity ratios (in order of the figures) of $1{\cdot}14$, $1{\cdot}18$, $1{\cdot}10$, $0{\cdot}98$, $1{\cdot}22$ and the first reattaching profiles appear with velocity ratios that are somewhat higher than the value for detachment in the same layer (see figures 23, 24 and 26). Separating boundary layers are however notoriously difficult flows in which to get reliable or consistent measurements. This data has been selected as the best available but may well contain errors. Taken as a whole the data conforms to the present proposals with a consistency remarkable in the analysis of separating flow, and while the correct value for the velocity ratio may well differ from $1{\cdot}18$ it is unlikely to be far from this value.

Further support for these proposals was sought by analysing layers that closely approached detachment (figures 28–31). Of the Stradford (1959) layers, flow 6 is shown as much closer to transitory detachment than flow 5 and this agrees with the equilibrium analysis of these layers by Schofield (1981).[2] As before, the skin friction distributions for all layers can be plausibly extrapolated to zero at or near $U_S/U_1 = 1{\cdot}18$.

3.3 Discussion

That detachment occurs at a universal value of H was a very early idea in boundary layer theory and has been a working rule of thumb by practising designers for a long time. The present work gives these ideas some theoretical basis but it also shows that separating and separated boundary layers are part of a continuous development of adverse pressure gradient layers which are governed by Schofield and Perry similarity and follow a unique locus of H, H_D versus U_S/U_1. Detachment, which occurs at a set position on the locus, has no effect on the outer flow similarity. A comparison of these results with other separation theories is interesting and instructive. It was Clauser (1956) who originally attacked the simple view that a boundary layer would separate at a universal value of H. He showed that H was a function of wall shear as well as pressure gradient and that for a given pressure gradient H could be greatly increased by a rough wall. His argument implied that in adverse pressure gradient flow a rough wall would bring on boundary layer detachment at a different value of H than in the corresponding smooth wall flow. However the data he employed to support his argument was confined to zero pressure gradient flow. Flow in strong adverse gradients, where boundary layer separation occurs, differs markedly from zero pressure gradient flow in that the effect of wall shear on the profile shape is very small.

1. Detached profiles in these layers were identified by surface flow visualization tests and/or the appearance of reversed flow near the wall in the mean profiles.

2. Only the downstream portions of these two layers can be considered as equilibrium layers.

This was shown in analyses of Schofield (1981, 1981*a*) and is supported by data presented in figures 32, 33 and 34. In these figures data from rough wall boundary layers approaching detachment in adverse pressure gradients show behaviour similar to the smooth wall data in figures 28–31, with skin friction curves extrapolating to zero near $U_S/U_1 = 1 \cdot 18$. The rough wall may bring a layer to separation in a shorter development distance but it does not alter the mean flow similarity nor apparently the detachment criterion. The error in the (Clauser) argument is to read across behaviour from zero pressure gradient layers into adverse pressure gradient layers in which a different velocity defect law (using a velocity scale unrelated to the wall shear) applied.

The present proposals imply a universal separation profile and in this it is similar to Coles' (1956) account of separation. Coles' wake hypothesis envisaged a separating layer as one in which the logarithmic law of the wall shrunk towards the wall so that in increasing proportion of the profile was described by his wake function until at detachment the wake extended to the wall (giving $H = 4 \cdot 2$ at detachment). Similarly Simpson *et al.* (1977) and Schofield (1981) envisaged the separation process as a contraction of the logarithmic law to the wall with a corresponding extension of the half power law equation (5) towards the wall. As the distance from the wall to the tangential junction (y_c) of the two laws was given by Schofield and Perry to be

$$y_c = 18 \cdot 6\, c_f'\, B \frac{U_1^2}{U_s^2} \tag{10}$$

the theory predicted that at detachment y_c was zero, implying no logarithmic law and a half power region extending to the wall. Then for the mean velocity to be zero at the wall U_s/U_1 had to have a value of 1 by equation (5). Thus detachment was predicted in both papers at $U_s/U_1 = 1$ ($H = 2 \cdot 4$) which of course does not agree with the evidence presented above. There are two flaws in this argument. Firstly no account has been taken of the viscous sublayer and, while this is unimportant when well attached boundary layers are being considered, it is important in considering mean velocities very near the wall. Secondly the premise on which equation (10) is based, a tangential junction between the two laws, does not apparently hold for layers near detachment or reattachment (see for instance profiles either side of the separation bubble in figure 2a). For these reasons the theoretical prediction of detachment at $U_s/U_1 = 1$ can only be considered as a first approximation.

Finally if we look at how the proposed criterion relates to the theoretical limit for attached equilibrium layers[1] recently established by Schofield (1981), then we can learn something of the separation behaviour of layers in moving equilibrium. Figure 35 shows the attachment detachment boundary as a line of $c_f' = 0$ on axes of inverse velocity ratio (U_1/U_s) and pressure gradient strength (m).* In figure 35a the positions of observed precise equilibrium layers near detachment have been plotted. It seems reasonable that boundary layers separating in moving equilibrium would follow the locus defined by the positions of these equilibrium layers and shown in the figure as a dotted line. The extrapolation of this line cuts the $c_f' = 0$ line at a value of U_s/U_1 near $1 \cdot 18$ and is therefore consistent with the preceding work. The trajectory also implies that separating layers in moving equilibrium approach detachment with a decreasing local pressure gradient. At first sight this may appear a surprising result but empirical evidence supports it. Both Simpson *et al.* (1977, 1981) and Perry and Fairlie (1975) observed that as detachment was approached the pressure gradient decreased quite rapidly. Schofield (1983) who applied the the severest pressure gradient available (a normal shock wave) to a boundary layer found that detachment still occurred at a position of low local pressure gradient. In all cases the pressure gradient was reduced near separation by the mechanism of rapid boundary layer thickening causing large local deviations in the streamlines. In the case of a shock wave separating the boundary layer, the shock pressure rise is distributed along the wall through the subsonic portion of the layer, the thickness of which is increased by the interaction. Thus, during separation the sheared and unsheared flow interact to decrease the local pressure gradient. We also know that as layers approach detachment the velocity ratio U_s/U_1 increases (see figures 21 to 34). Thus it is to be expected that the trajectory of a separating layer is one of increasing U_s/U_1 and m.

1. Equilibrium layers are defined here as in Schofield (1981) as layers with a constant value of U_s/U_1 throughout their development.

* m is the index of the free stream velocity variation ($U_1 \propto x^m$). It becomes more negative as the pressure gradient becomes more adverse.

similar to the locus shown in figure 35a. If the separating layers considered in this work are analysed using the assumption that they are in moving equilibrium near separation, then their separating trajectories are found to closely follow the locus of equilibrium layers near detachment. Examples are shown in figures 35b, 35c, and 35d. All three trajectories cross the theoretical detachment line ($c_f' = 0$) near $U_s/U_1 = 1\cdot18$ or $m \simeq -0\cdot2$. This work then suggests that layers which separate in moving equilibrium detach at the same local pressure gradient with the same mean profile shape. The trajectory of Schofield's layer shows reattachment occurring at slightly larger values of U_s/U_1 and m than detachment. This is consistent with the previous work (figure 26).

4. CONCLUSIONS

1. The Schofield and Perry similarity for adverse pressure gradient boundary layers applies to detached flow as well as attached flow. The similarity applies only to the forward flowing portion of a detached layer and requires the origin of the similarity relation to be moved from the wall to the zero mean velocity streamline in the flow. The similarity velocity ratio (U_s/U_1) varies continuously along a separating or reattaching layer and it seems that the only change brought about by detachment is that the backflow provides a different inner (wall) matching condition for the outer similarity.
2. The reversed flow does not scale with the forward flow similarity parameters nor with wall variables, probably because it is affected by downstream flow conditions. An improvement on the similarity proposed for this region by Simpson *et al.* (1981) is to use the total backflow thickness as the similarity length scale.
3. The logarithmic law of the wall is valid immediately after reattachment. As Simpson's results show that the same law is valid in a separating layer, at least up to the position of instantaneous flow reversals, it follows that the entire mean flow field of a separating or reattaching boundary layer can be accurately described in terms of:
    the Schofield and Perry defect law;
    the law of the wall, and
    the reversed flow similarity demonstrated here.
4. The extended validity of the Schofield and Perry defect law implies a unique progression of mean velocity profile shapes up to and through separation. This progression is given by

$$H \text{ or } H_D = \frac{1}{1-0\cdot58\, U_s/U_1}.$$

5. Turbulent boundary layers separating from surfaces of small curvature appear to detach with a universal mean velocity profile shape. This mean profile shape can be defined by $U_s/U_1 = 1\cdot18$ and has a shape factor of $3\cdot2$. The same conclusion apparently applies to reattachment although limited evidence suggests that reattaching profiles have a slightly higher value of U_s/U_1.
6. Layers approaching separation in moving equilibrium do so along trajectories that closely follow a locus joining the positions of observed equilibrium layers near detachment. These trajectories cross the theoretical detachment condition near the same point, implying that layers in moving equilibrium detach at the same local pressure gradient ($m \approx -0\cdot2$) with the same profile shape ($U_s/U_1 \approx 1\cdot18$).

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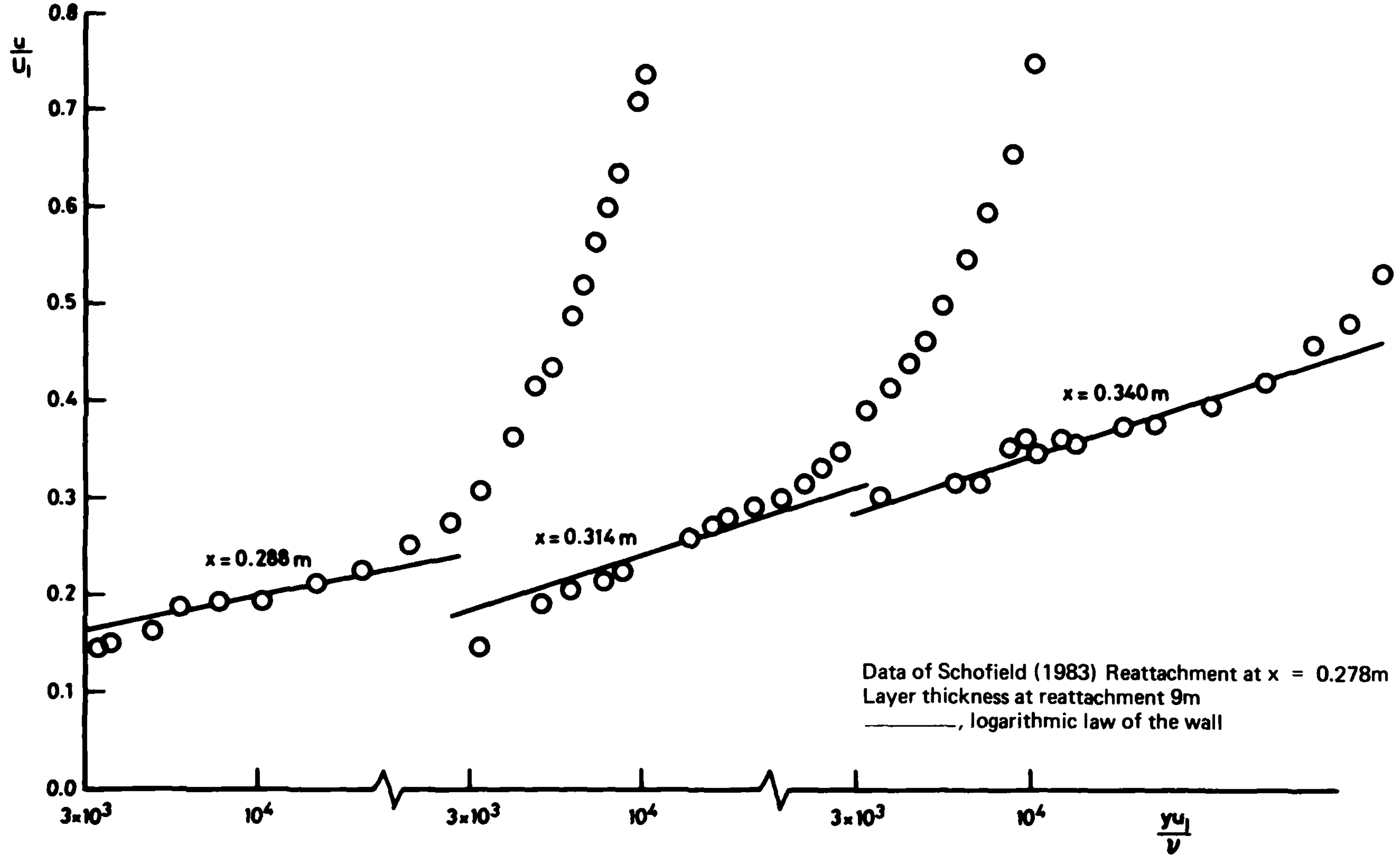
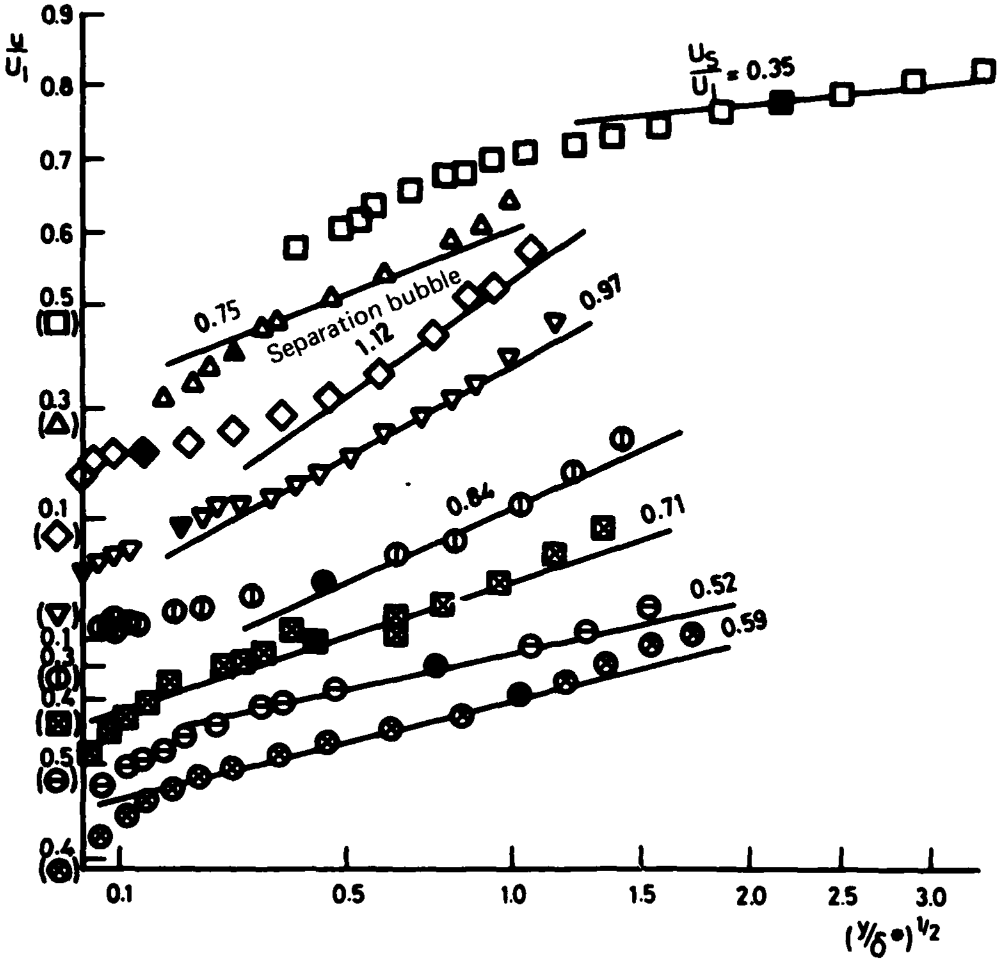


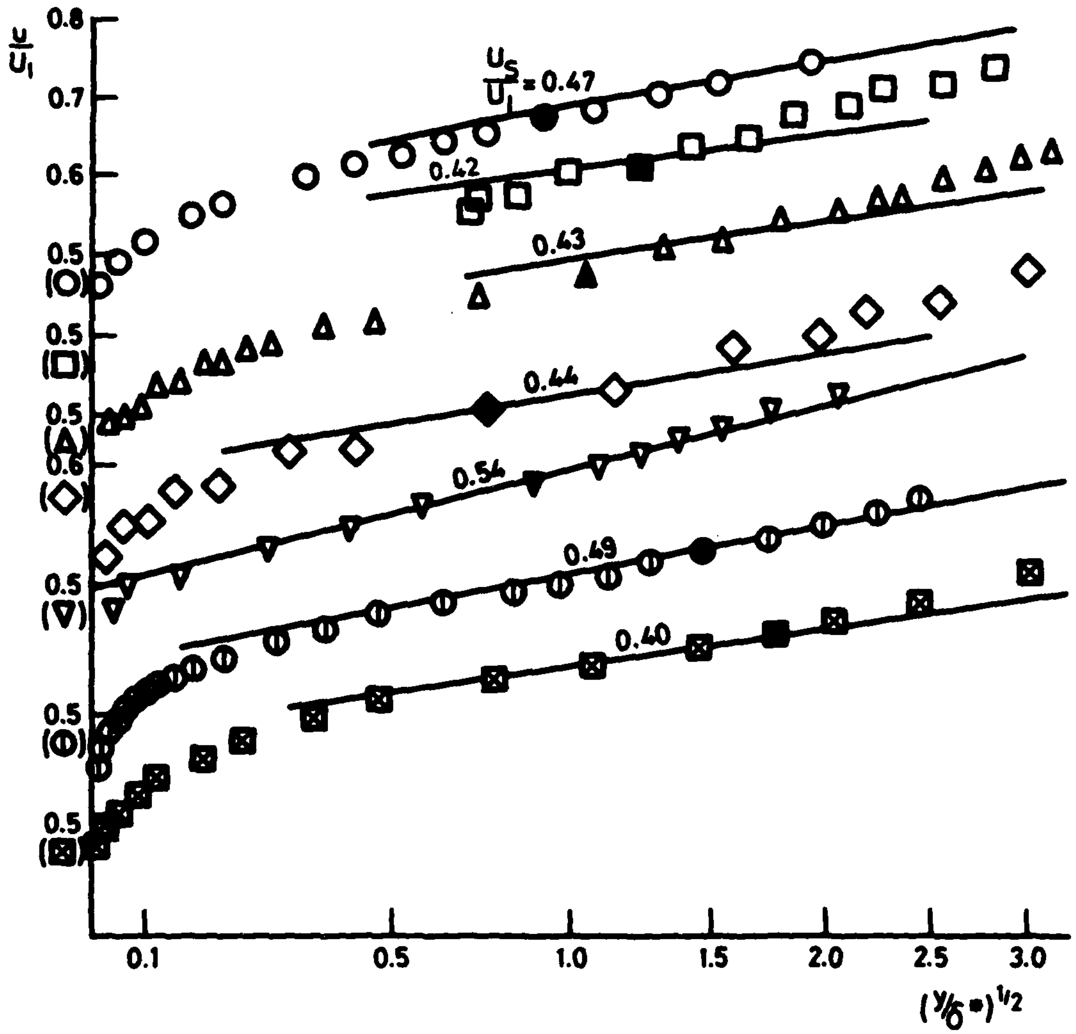
FIG. 1 LOGARITHMIC LAW OF THE WALL AFTER REATTACHMENT



□	0.2119m
△	0.2254m
◇	0.2884m
▽	0.3143m
⦶	0.3397m
⊠	0.3752m
⊖	0.4031m
⊗	0.4336m

Solid symbol is last point on logarithmic law of the wall

FIG. 2(a) HALF POWER DISTRIBUTIONS
Results of Schofield (1983)
Layer S ____, equation 5



○	0.5860m
□	0.7375m
△	0.8896m
◇	1.0423m
▽	1.1943m
Φ	1.3471m
⊠	1.5756m

Solid symbol is last point on logarithmic law of the wall. Data points have been omitted for clarity

FIG. 2(a) Concluded

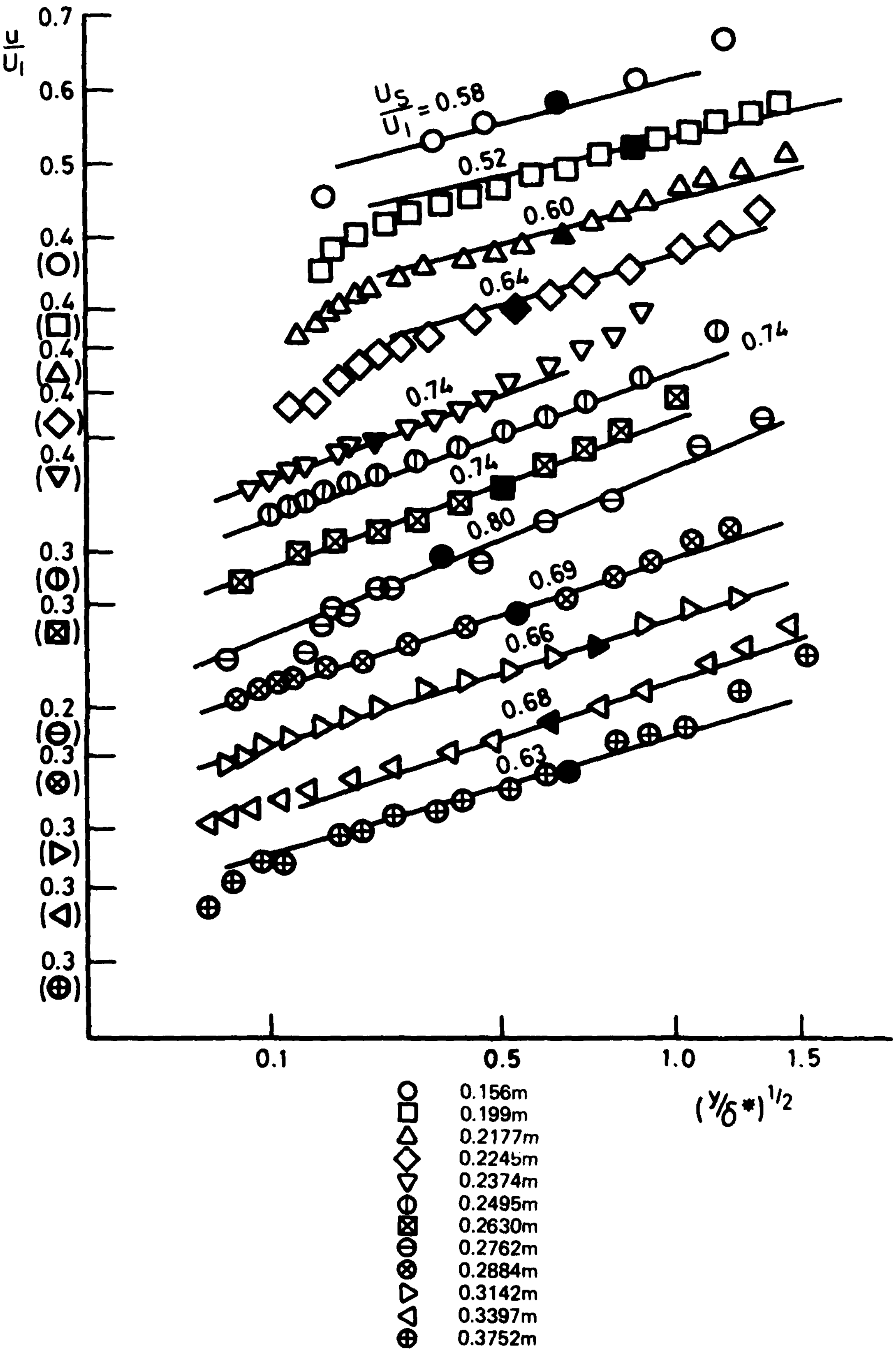
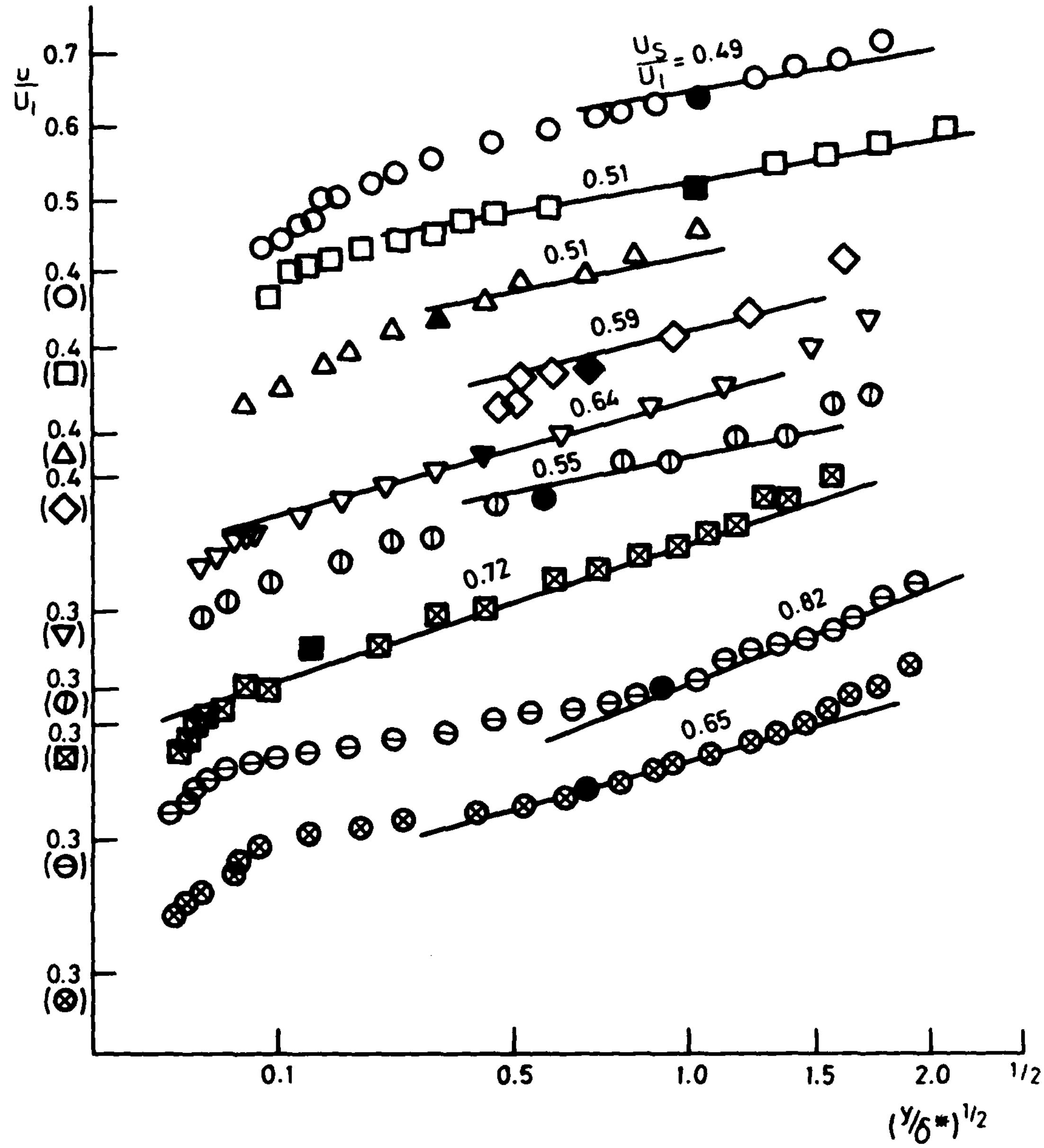


FIG. 2(b) HALF POWER DISTRIBUTIONS

Results of Schofield (1983)

Layer L ______, equation 5



○ 0.4031m
□ 0.4336m
△ 0.5860m
◇ 0.7375m
▽ 0.8896m
⦶ 1.0423m
⊠ 1.1943m
⊖ 1.3471m
⊗ 1.4995m

Solid symbol is last point on logarithmic law of the wall.
Points omitted near wall and elsewhere for clarity.

FIG. 2(b) Concluded

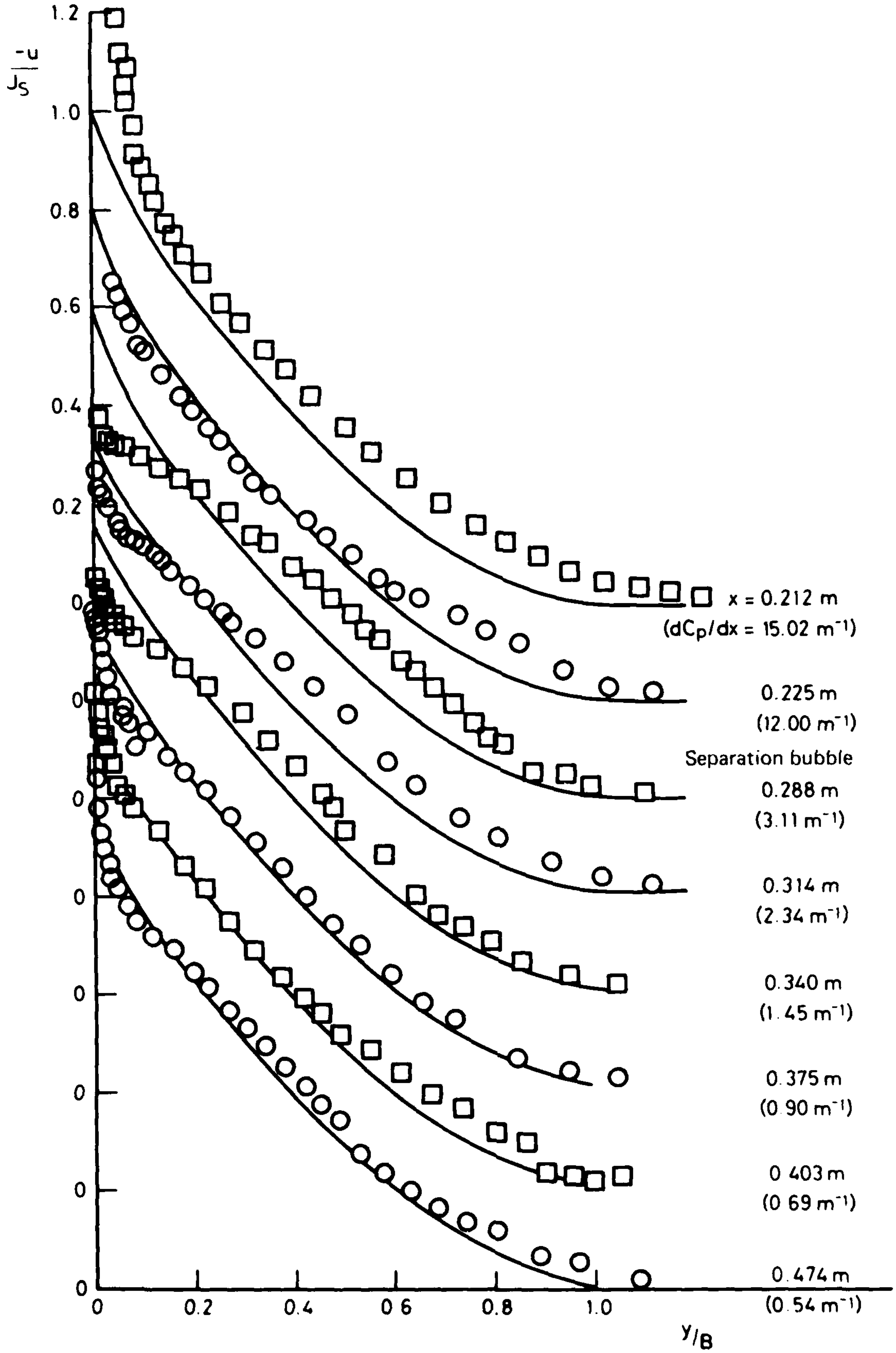


FIG. 3(a) SCHOFIELD & PERRY SIMILARITY
Results of Schofield (1983)
Layer S , equation 2

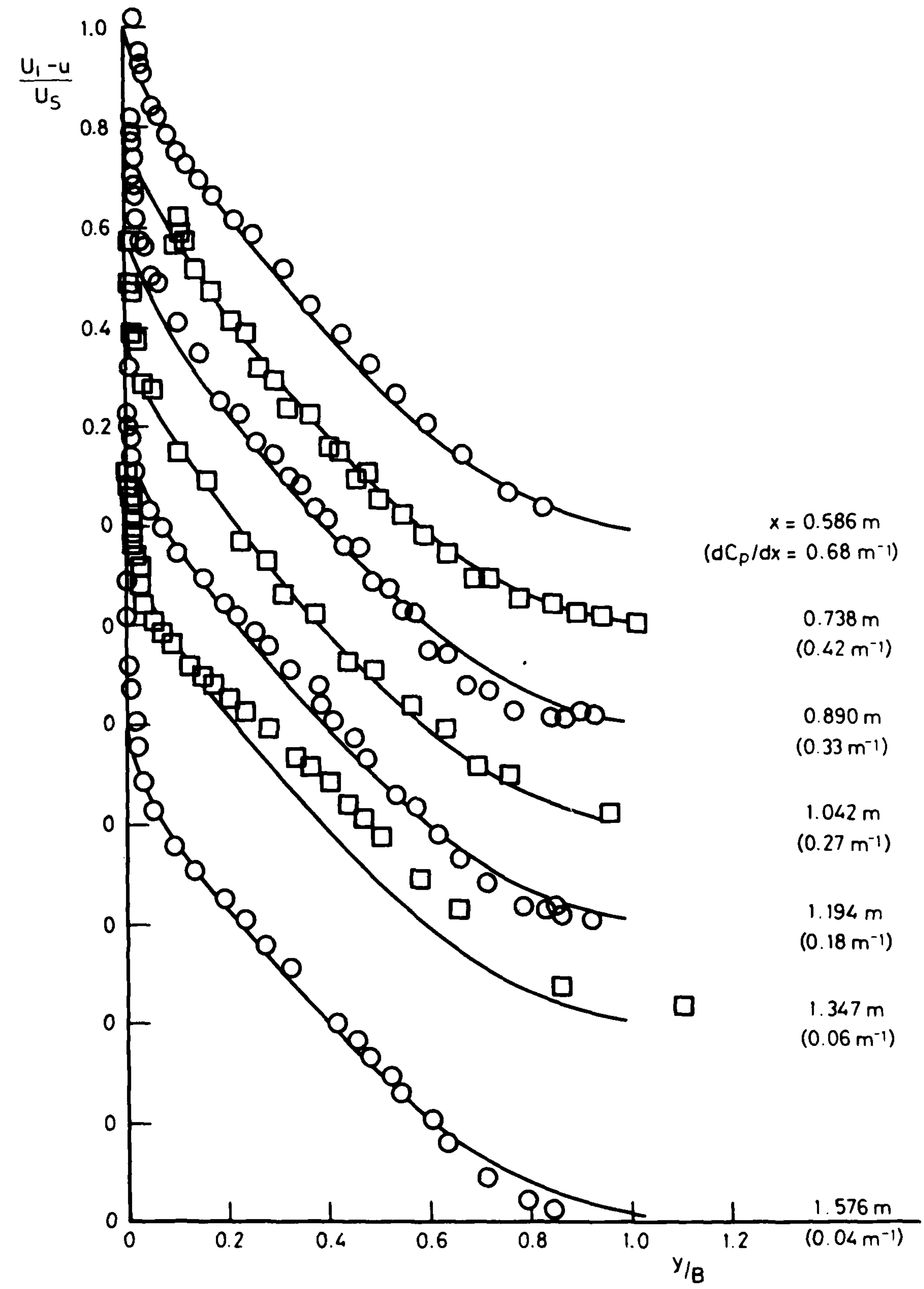


FIG. 3(a) Concluded

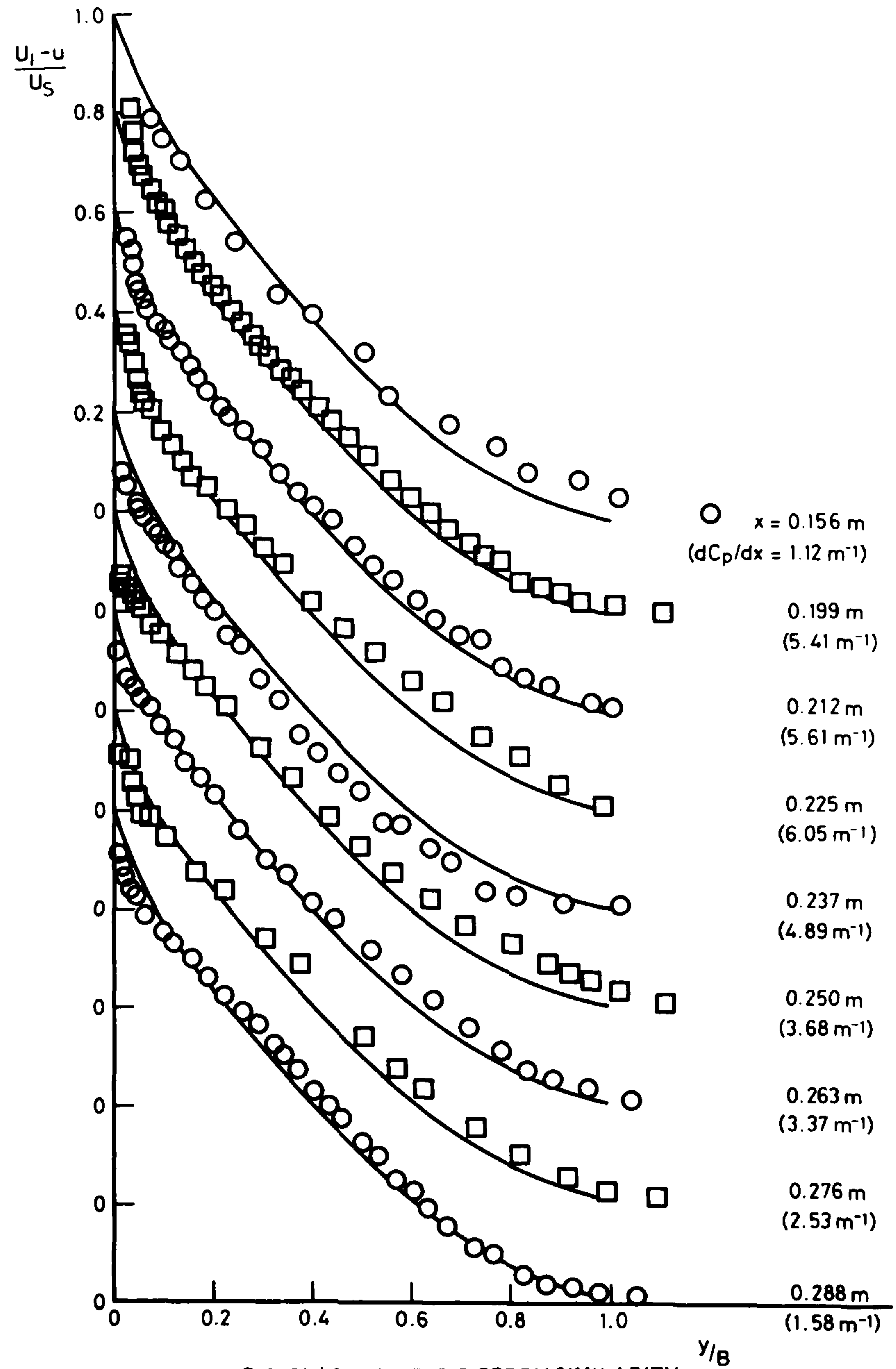


FIG. 3(b) SCHOFIELD & PERRY SIMILARITY
Results of Schofield (1983)
Layer L ——, equation 2

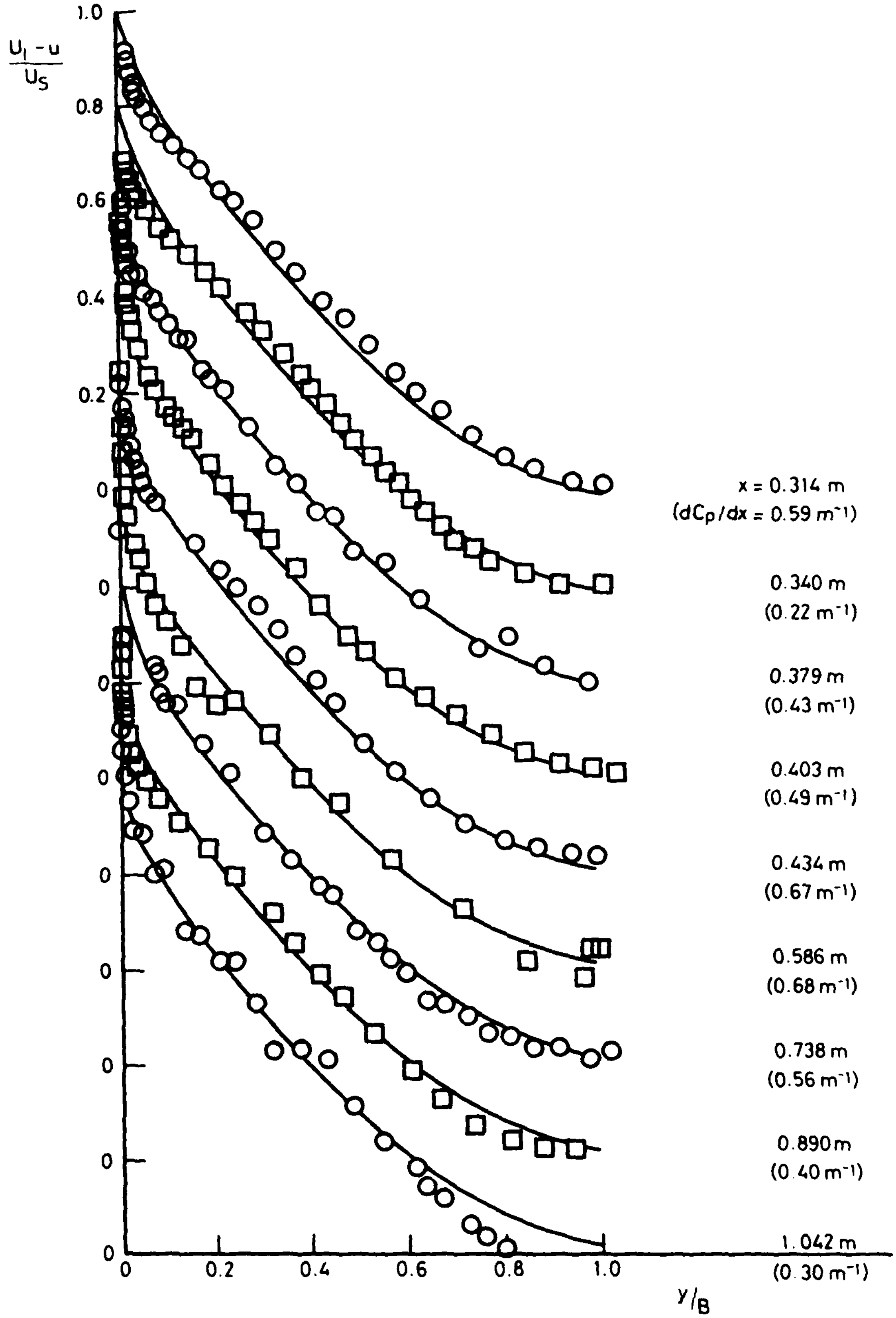


FIG. 3(b) Concluded

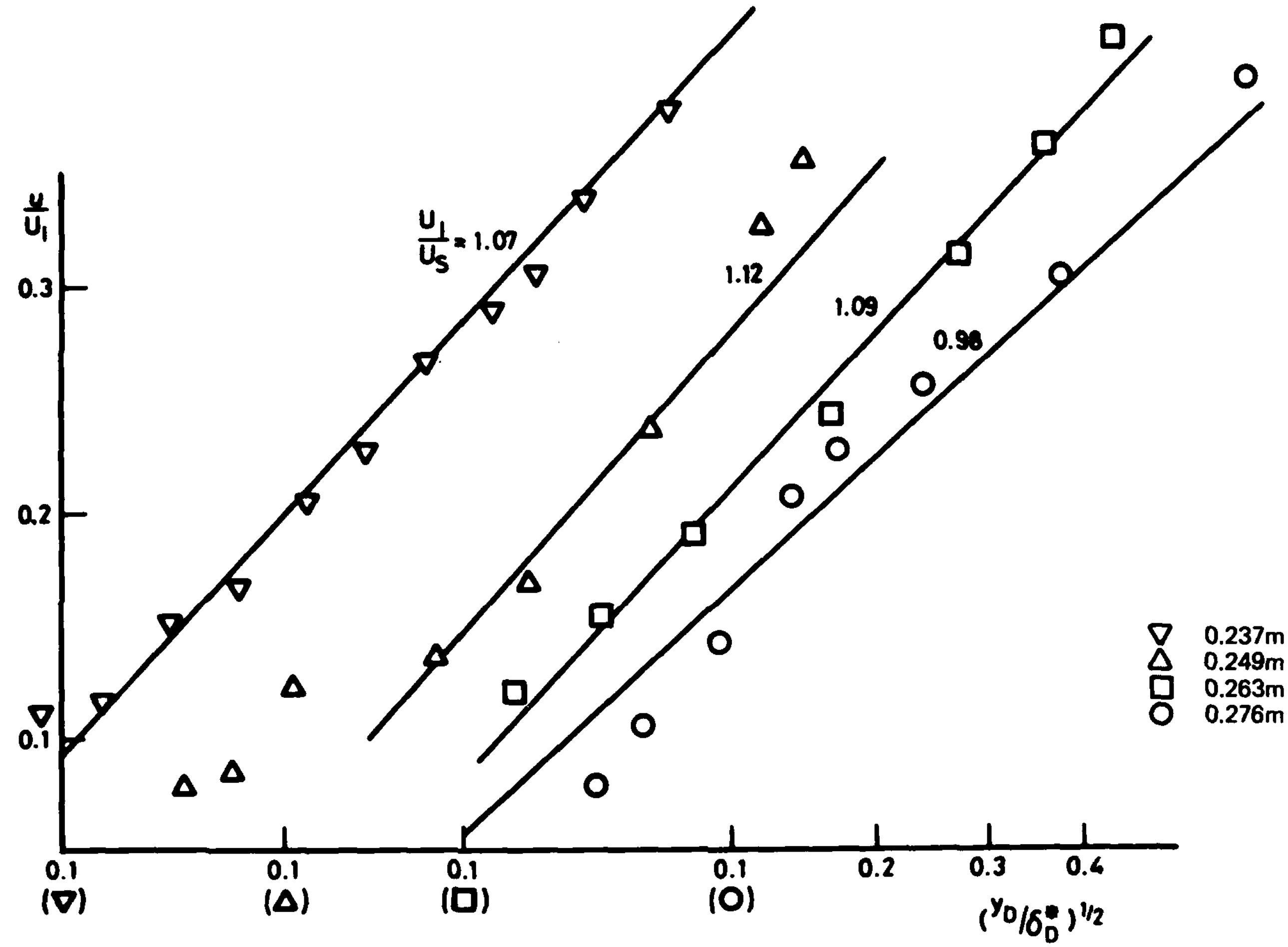


FIG. 4 HALF POWER DISTRIBUTIONS IN DETACHED PROFILES

Results of Schofield (1983)

———, equation 5

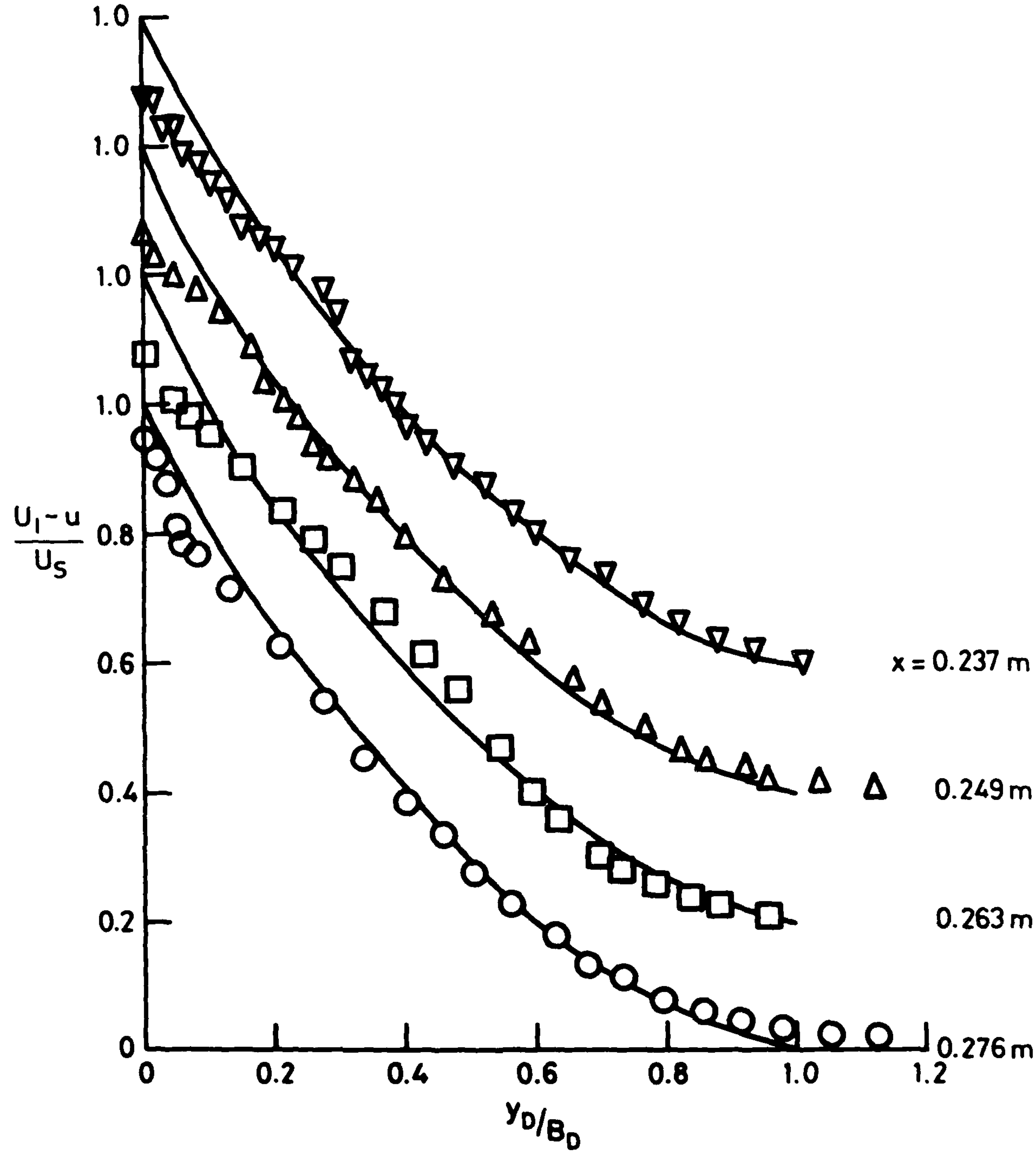


FIG. 5 SCHOFIELD & PERRY SIMILARITY IN SEPARATED FLOW
Results of Schofield (1983)
-, equation 2

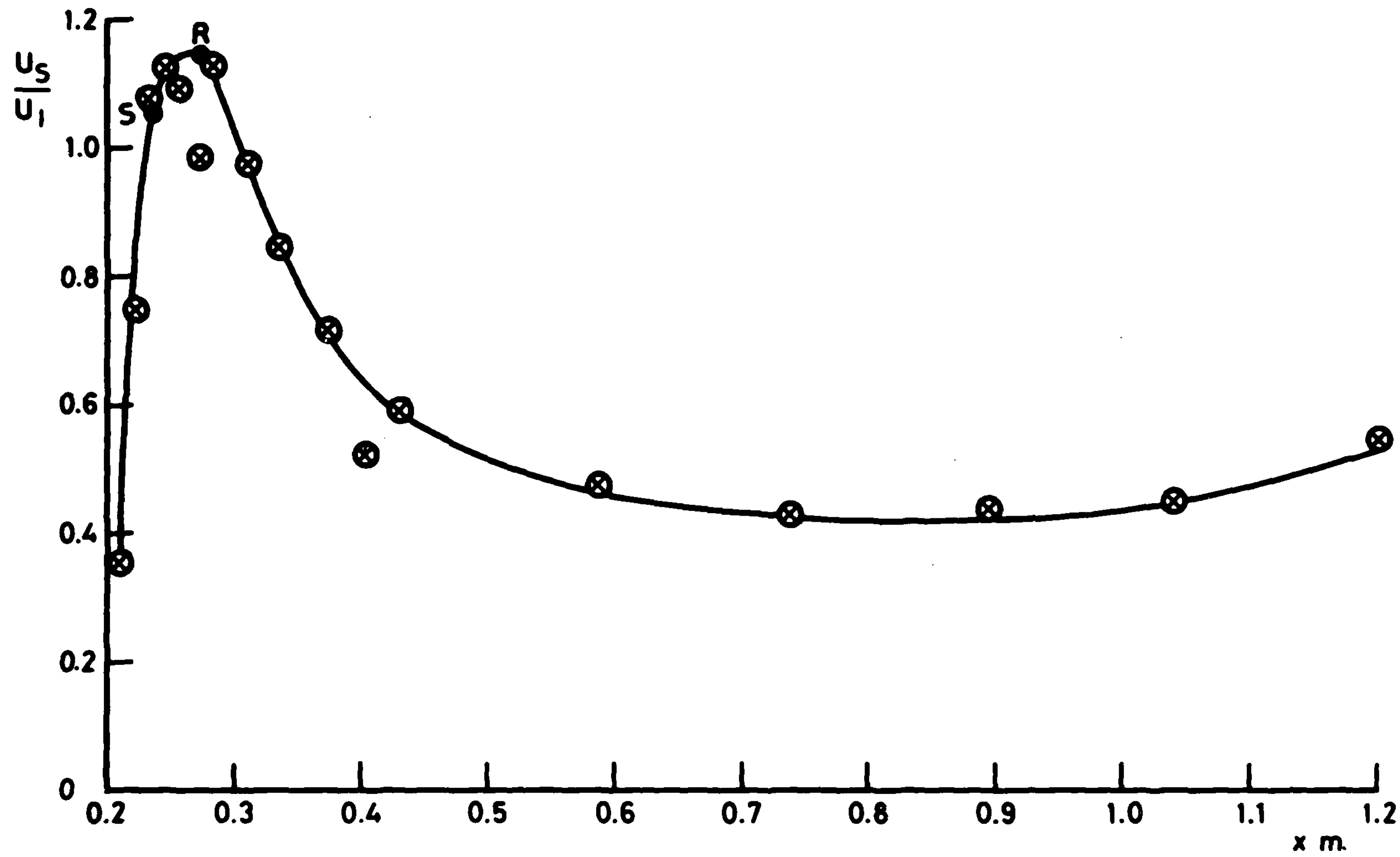


FIG. 6 VARIATION OF SCHOFIELD & PERRY VELOCITY RATIO

Results of Schofield (1983)
S, R indicate separation and
reattachment points respectively

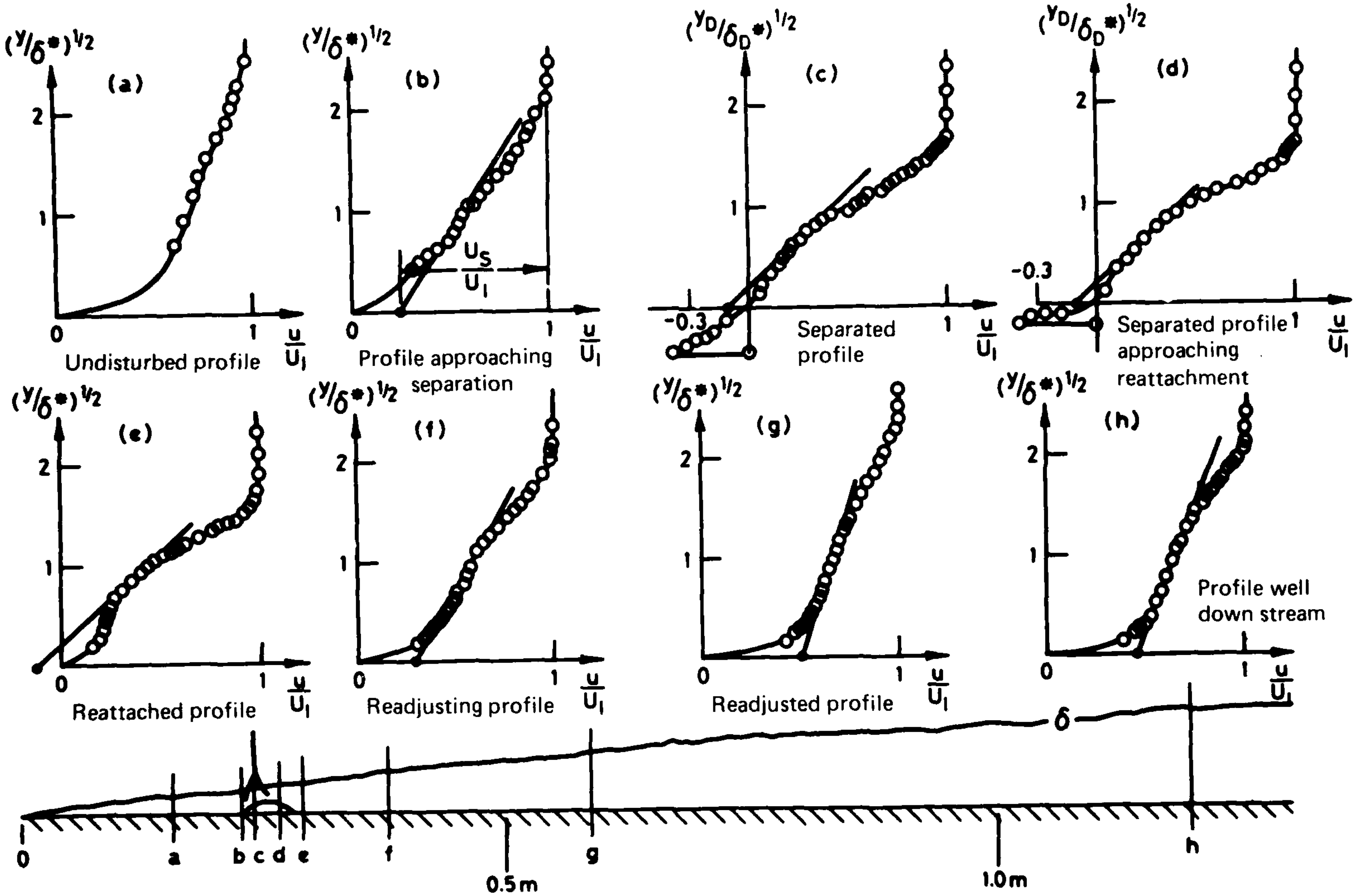
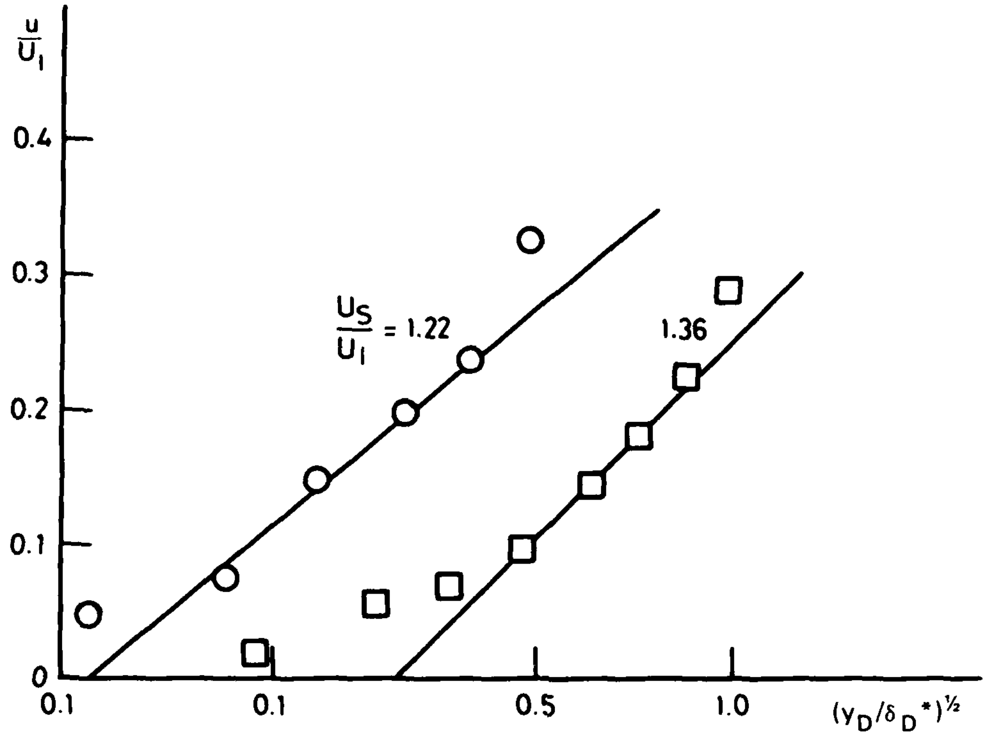


FIG. 7 VARIATION OF WALL MATCHING CONDITION ALONG A LOCALLY SEPARATED LAYER

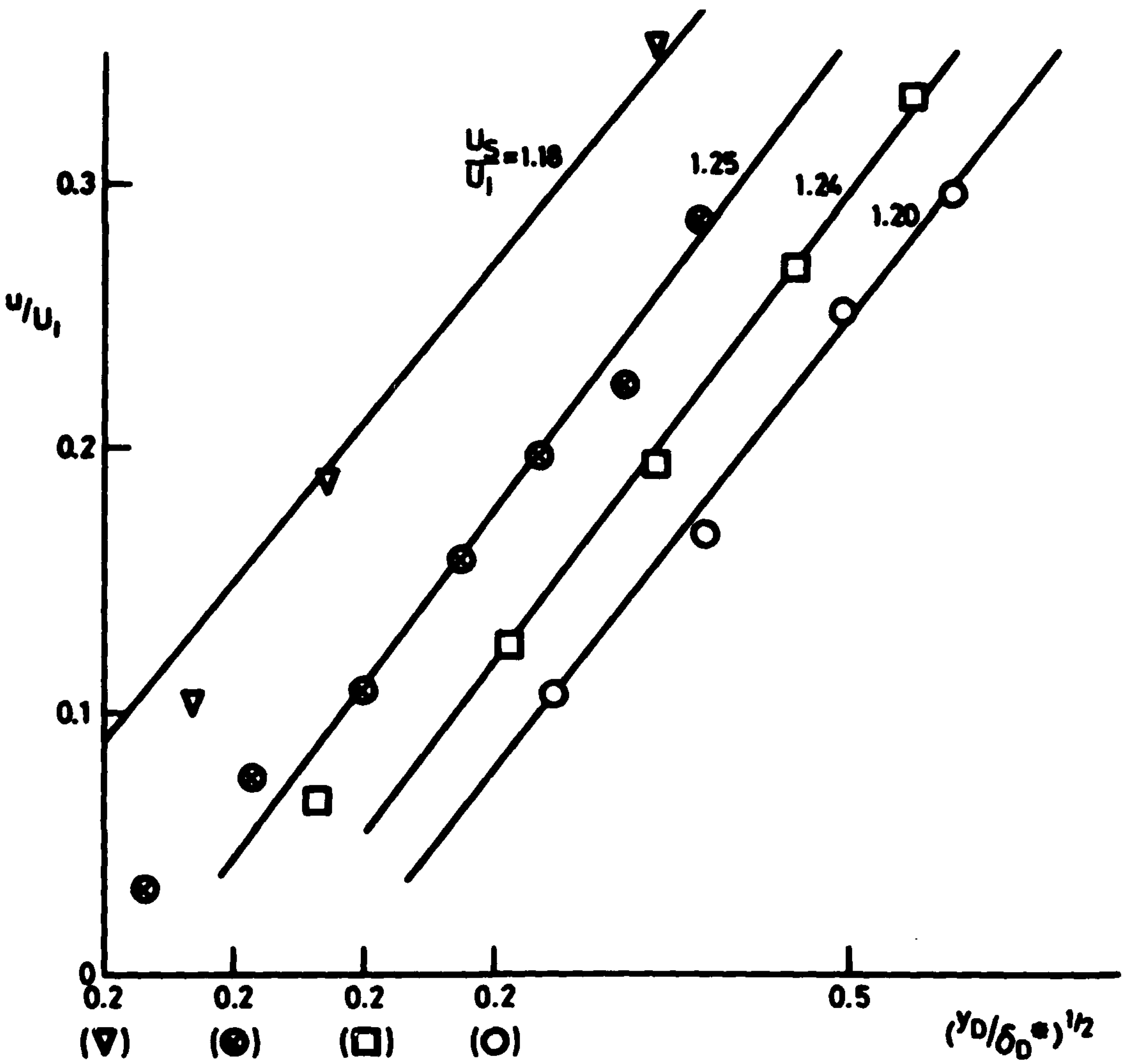
Results of Schofield (1983)

–, equation 5



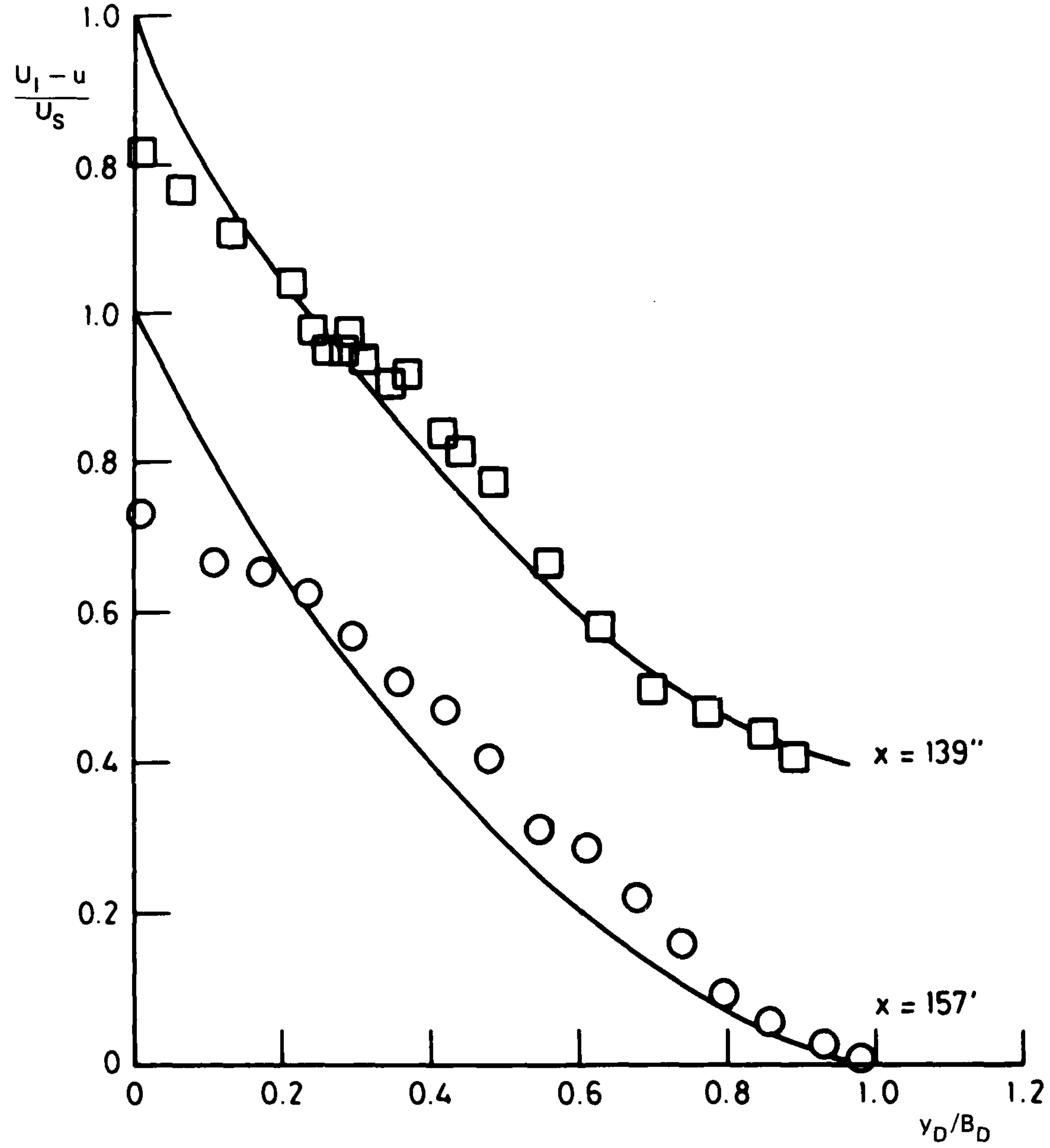
Simpson, Strickland & Barr (1977)
Separated flow
○ x = 139"
□ x = 157"
———, equation 5

FIG. 8 HALF POWER DISTRIBUTIONS



▽ x = 139″
⊗ x = 144″
□ x = 156″
○ x = 170″
———— , equation 5

FIG. 9 HALF POWER DISTRIBUTIONS
Simpson, Chew & Shiva Prasad (1981)
Separated flow



Simpson, Strickland & Barr (1977)
Separated flow
———, equation 2

FIG. 10 SCHOFIELD & PERRY SIMILARITY - - SEPARATED FLOW

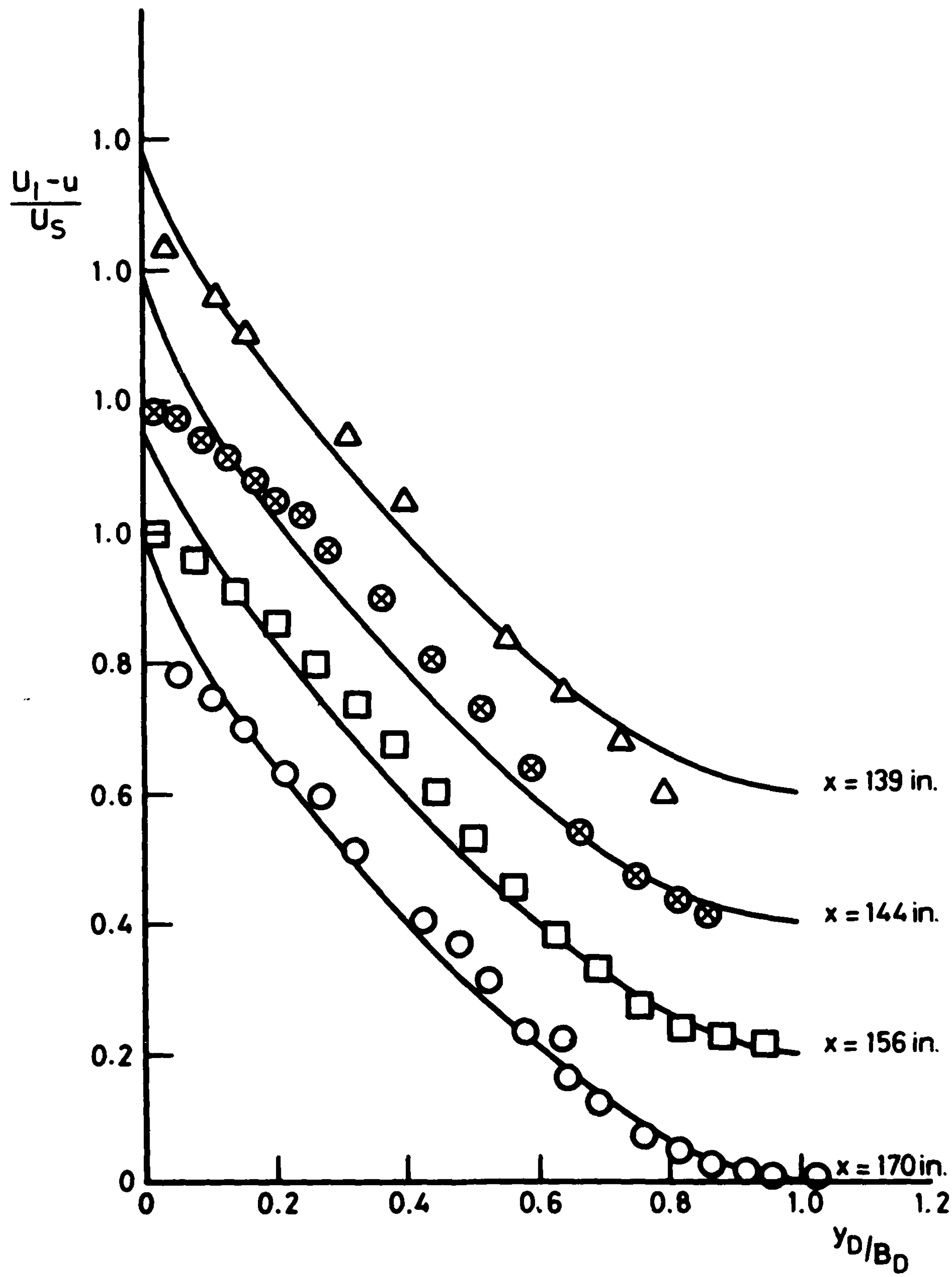


FIG. 11 SCHOFIELD & PERRY SIMILARITY - - SEPARATED FLOW

Simpson, Chew & Shiva Prasad (1981)

Separated flow

———, equation 2

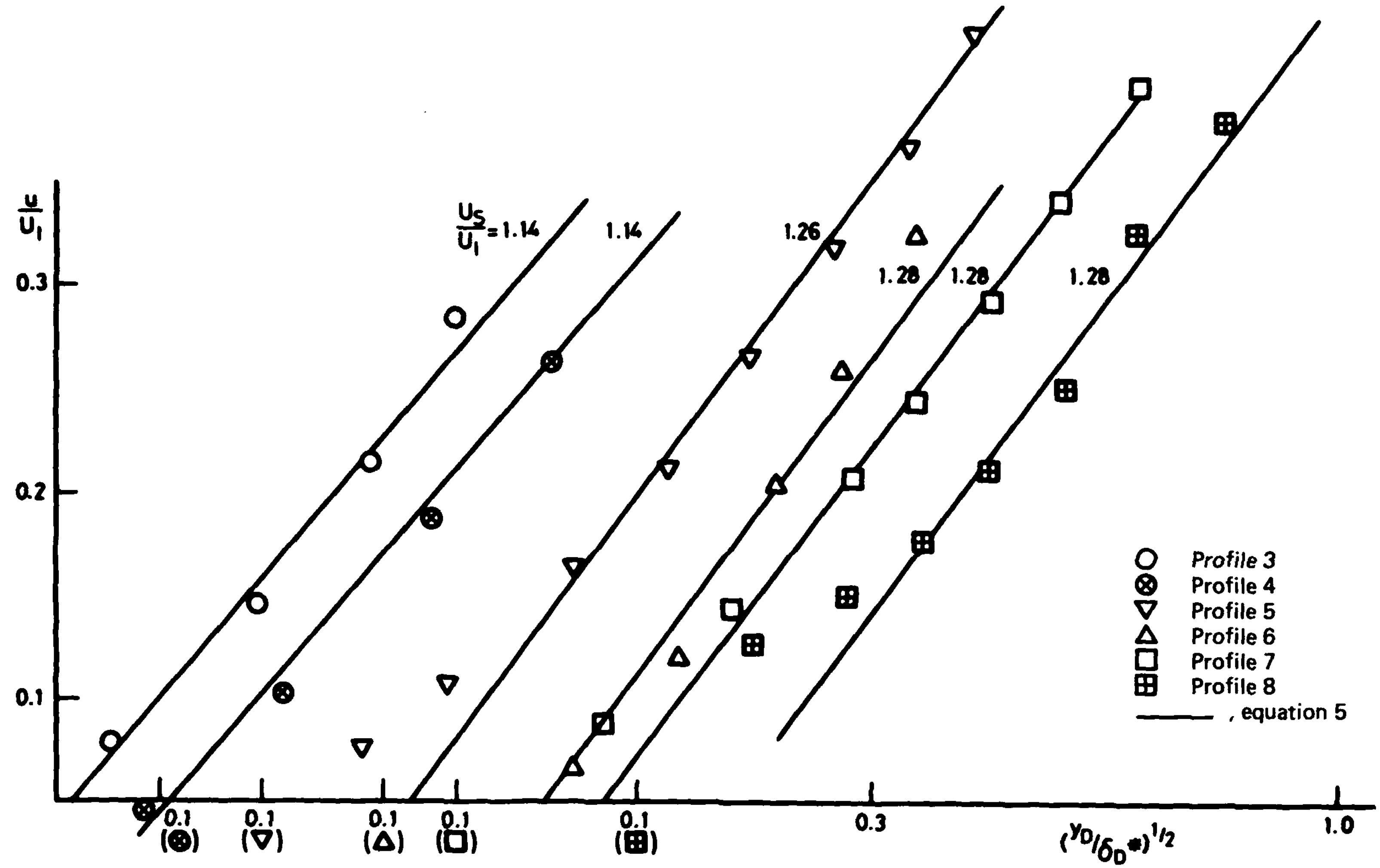


FIG. 12 HALF POWER DISTRIBUTIONS – SEPARATED FLOW
Seddon (1967) Basic interaction

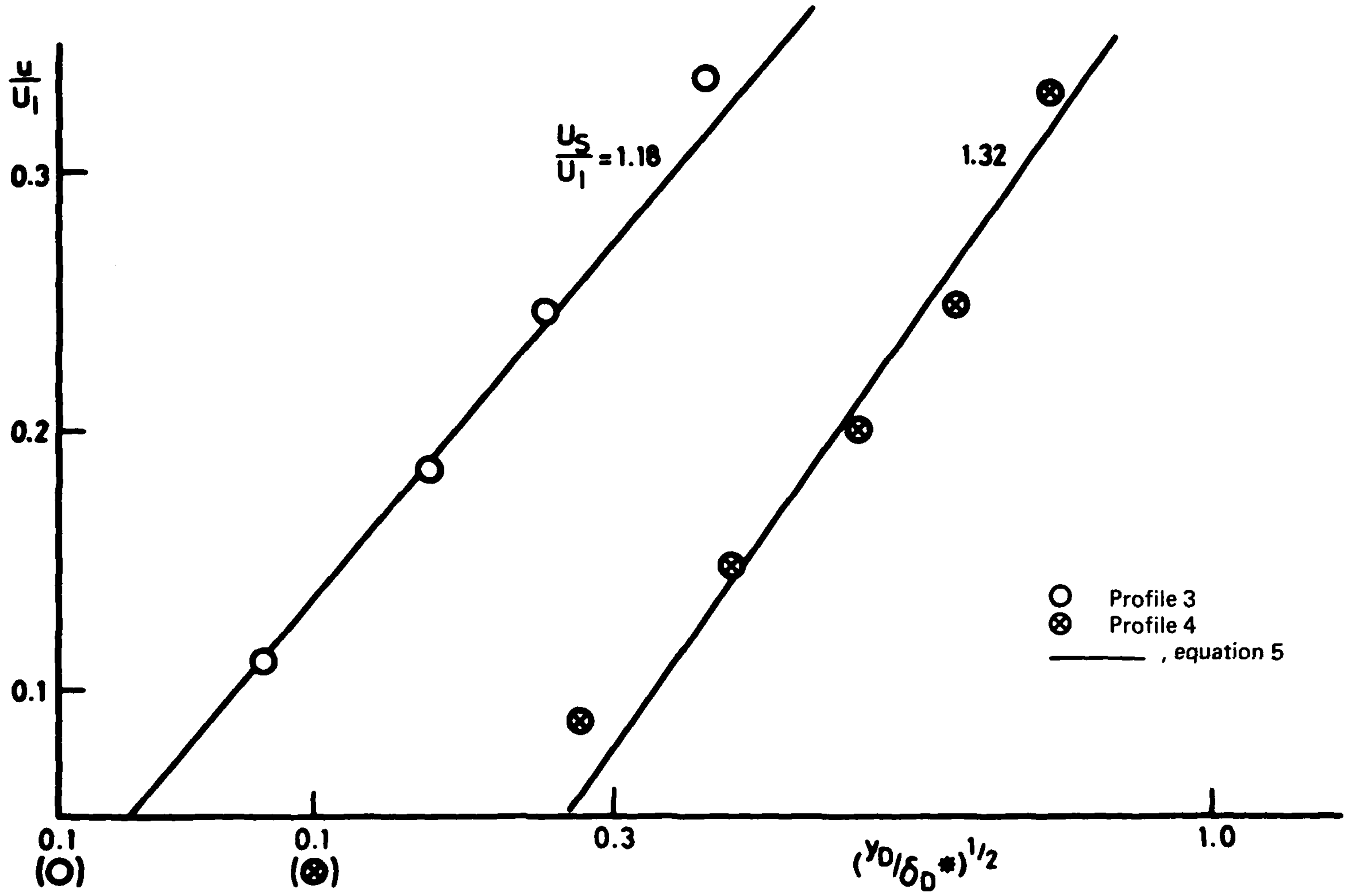


FIG. 13 HALF POWER DISTRIBUTIONS – SEPARATED FLOW
Seddon (1967) Modified interaction

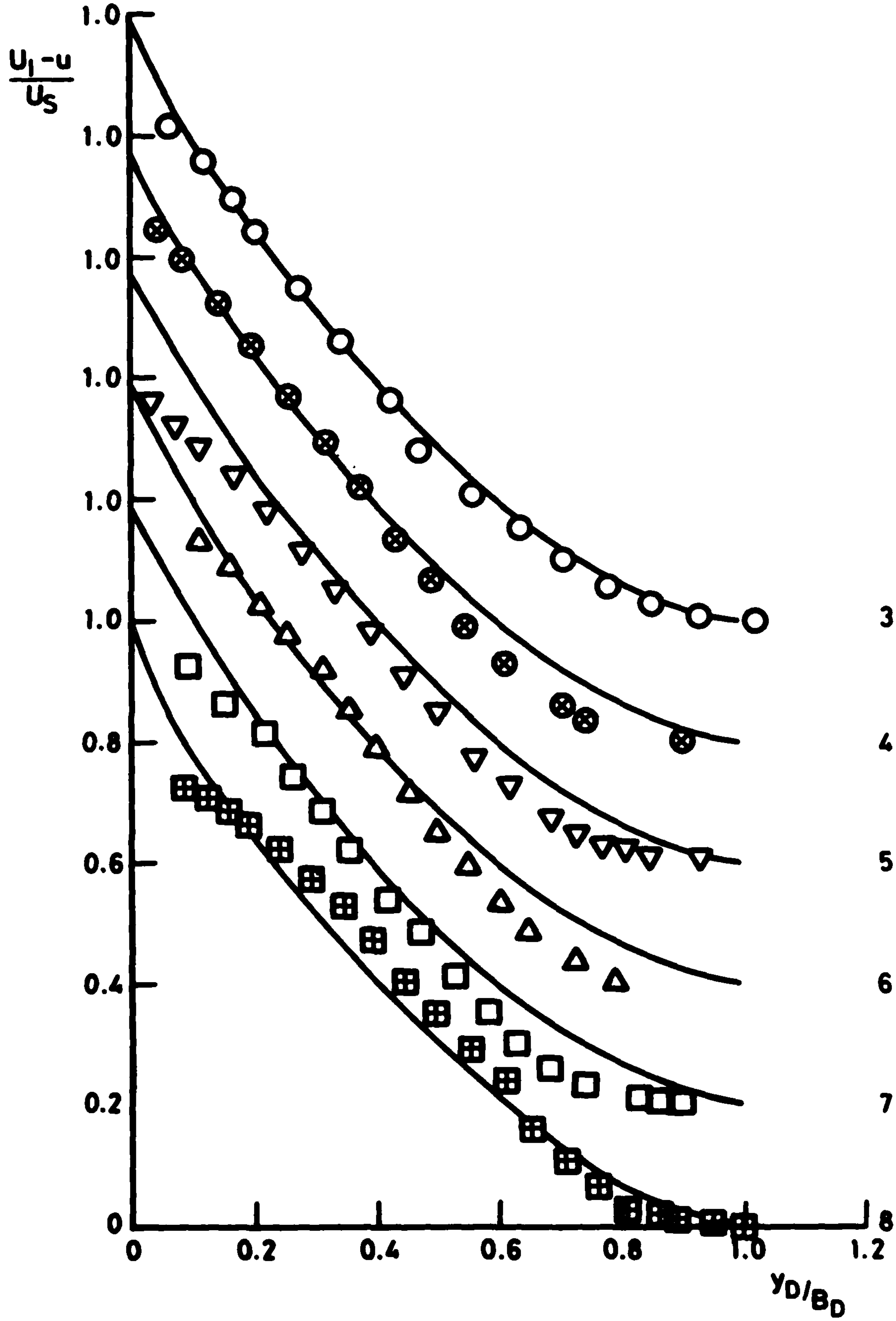


FIG. 14 SCHOFIELD & PERRY SIMILARITY – SEPARATED FLOW

Seddon (1967) Basic interaction

———, equation 2

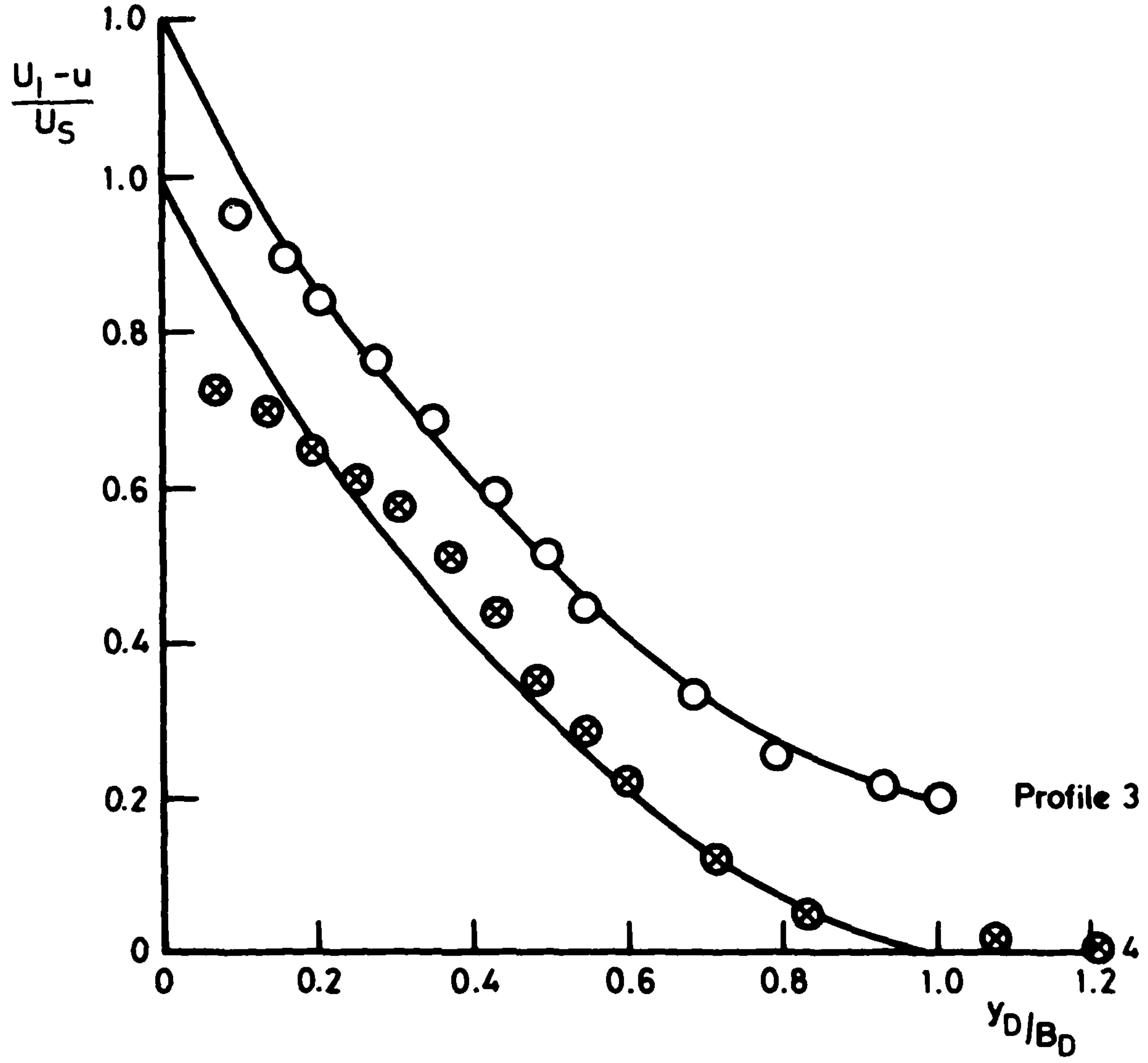
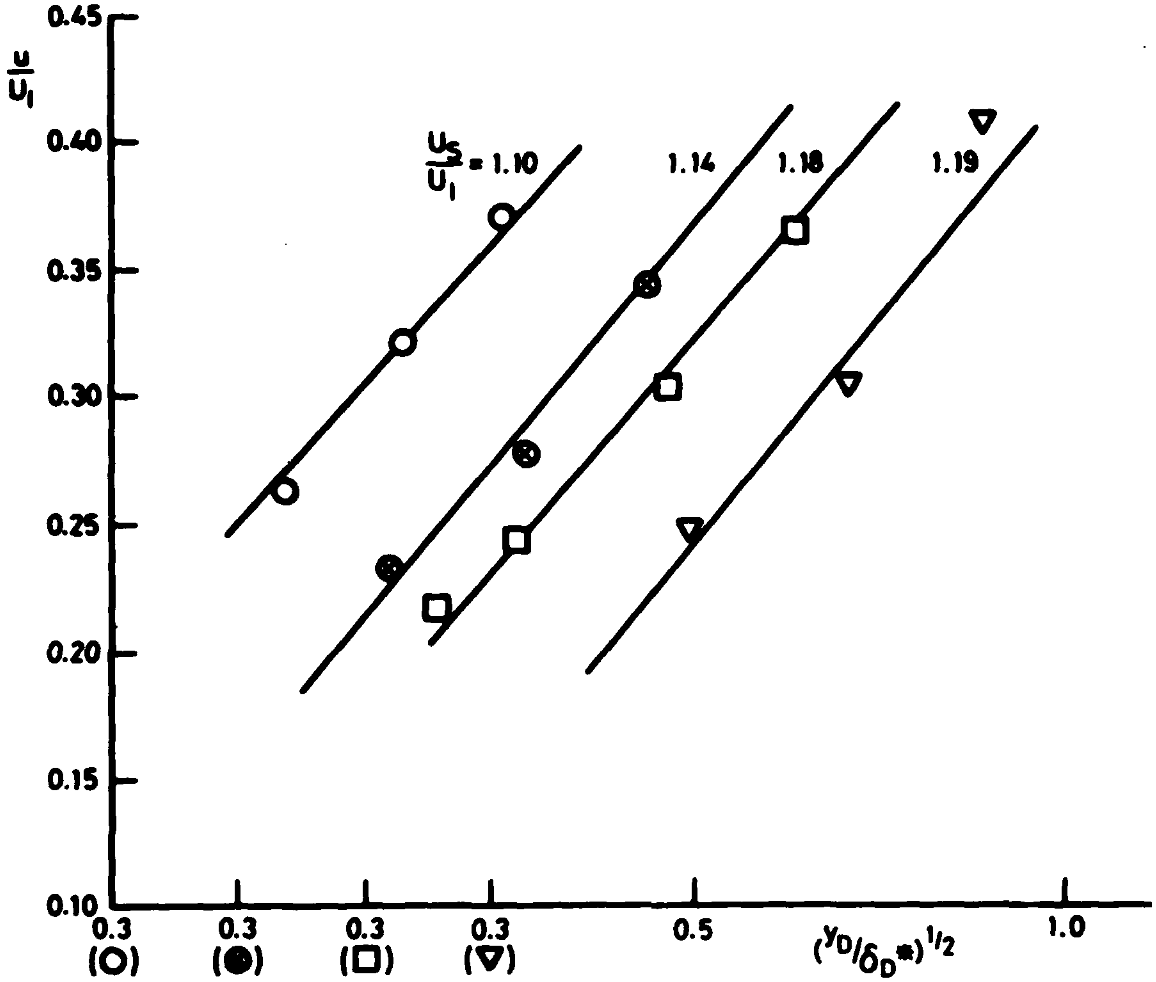


FIG. 15 SCHOFIELD & PERRY SIMILARITY – SEPARATED FLOW
Seddon (1967) Modified interaction
———, equation 2



x = 1.115m
x = 1.210m
x = 1.295m
x = 1.402m
——, equation 5

FIG. 16 HALF POWER DISTRIBUTIONS
Fairlie (1973) Separated flow

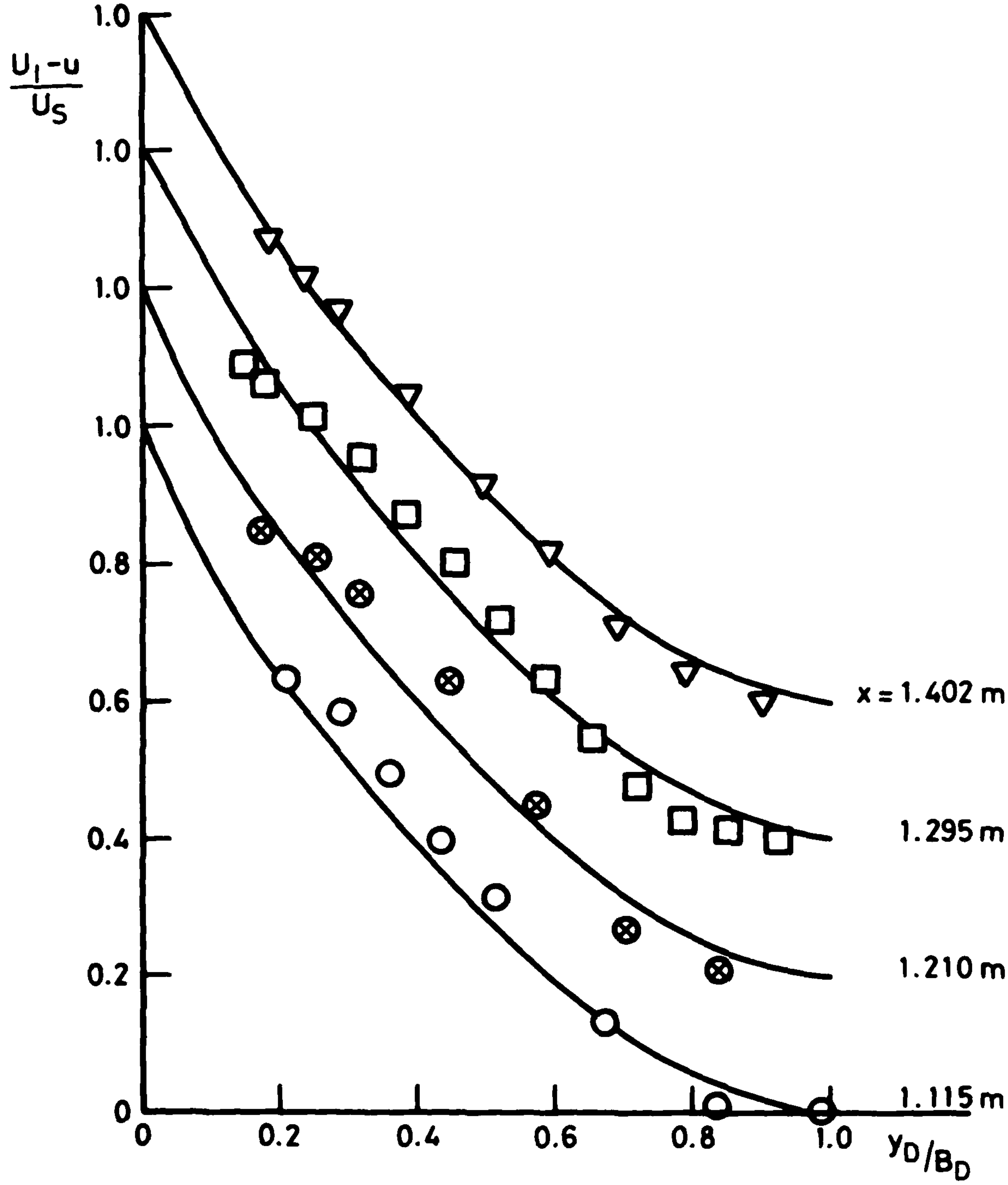


FIG. 17 SCHOFIELD & PERRY SIMILARITY – SEPARATED FLOW
Fairlie (1973)
———, equation 2

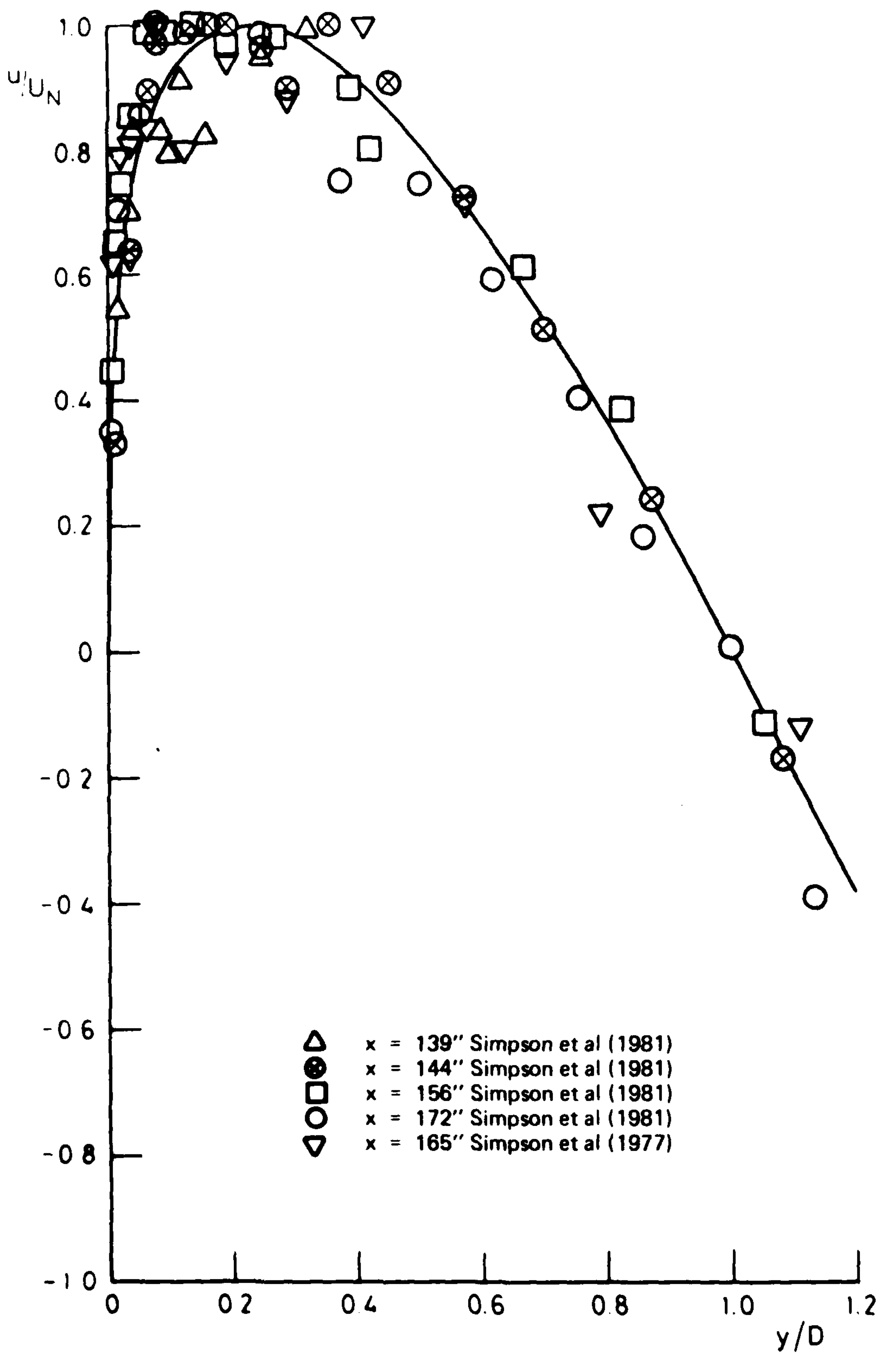
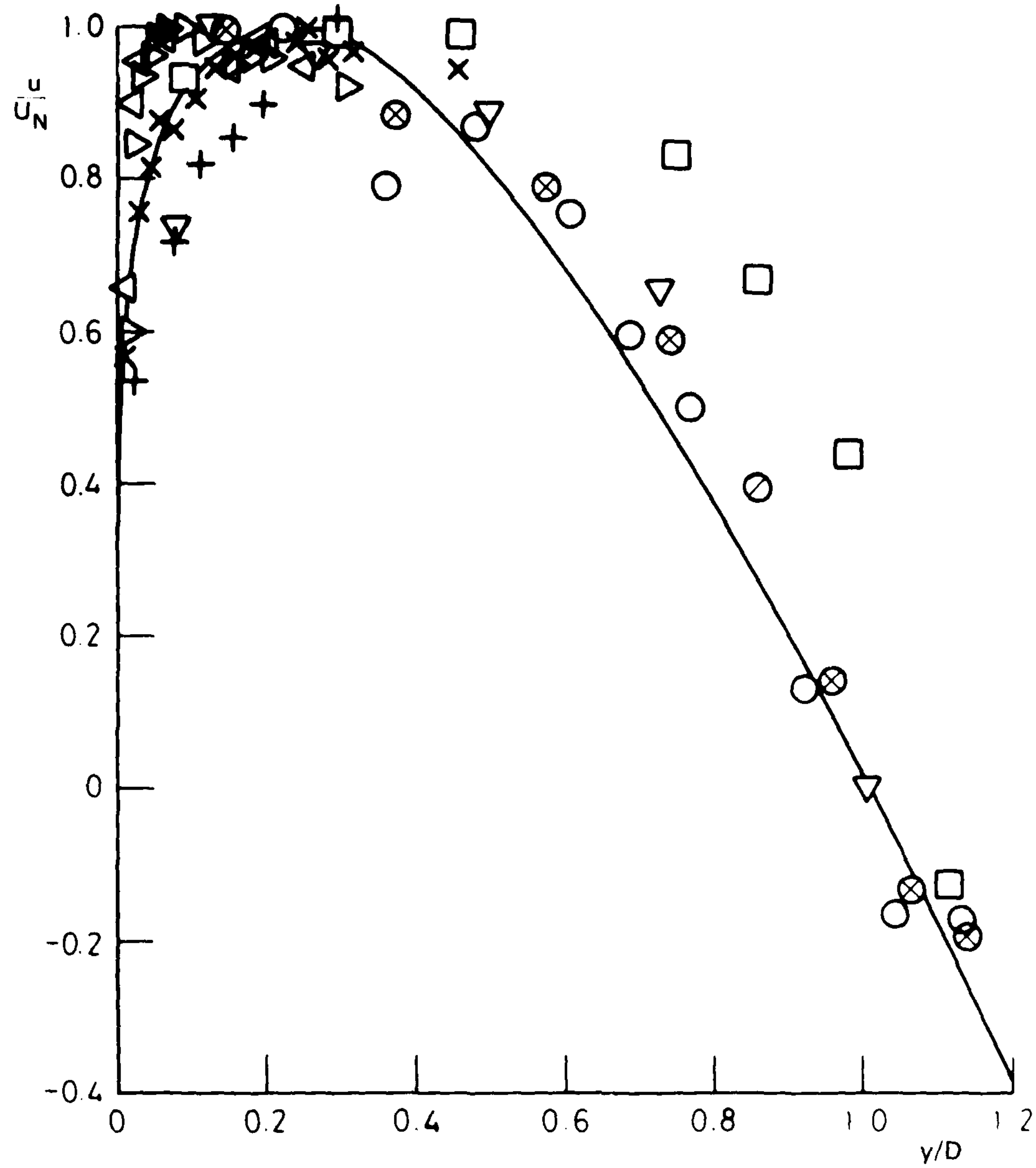


FIG. 18 MEAN BACK FLOW SIMILARITY. DATA MEASURED WITH LASER DOPPLER ANEMOMETRY



——, mean line from Figure 18

○ Schofield (1983) layer S   x = 0.237m
□ Schofield (1983) layer S   x = 0.263m
⊗ Schofield (1983) layer S   x = 0.276m
data for x = 0.249m not included as U_N not accurately known.
△ Seddon (1967) station 5
+ Fairlie (1973)
× Fairlie (1973)
▷ Fairlie (1973)
◁ Fairlie (1973)

FIG. 19 MEAN BACK FLOW SIMILARITY
(b) Data measured with pitot tubes or hot wire anemometers

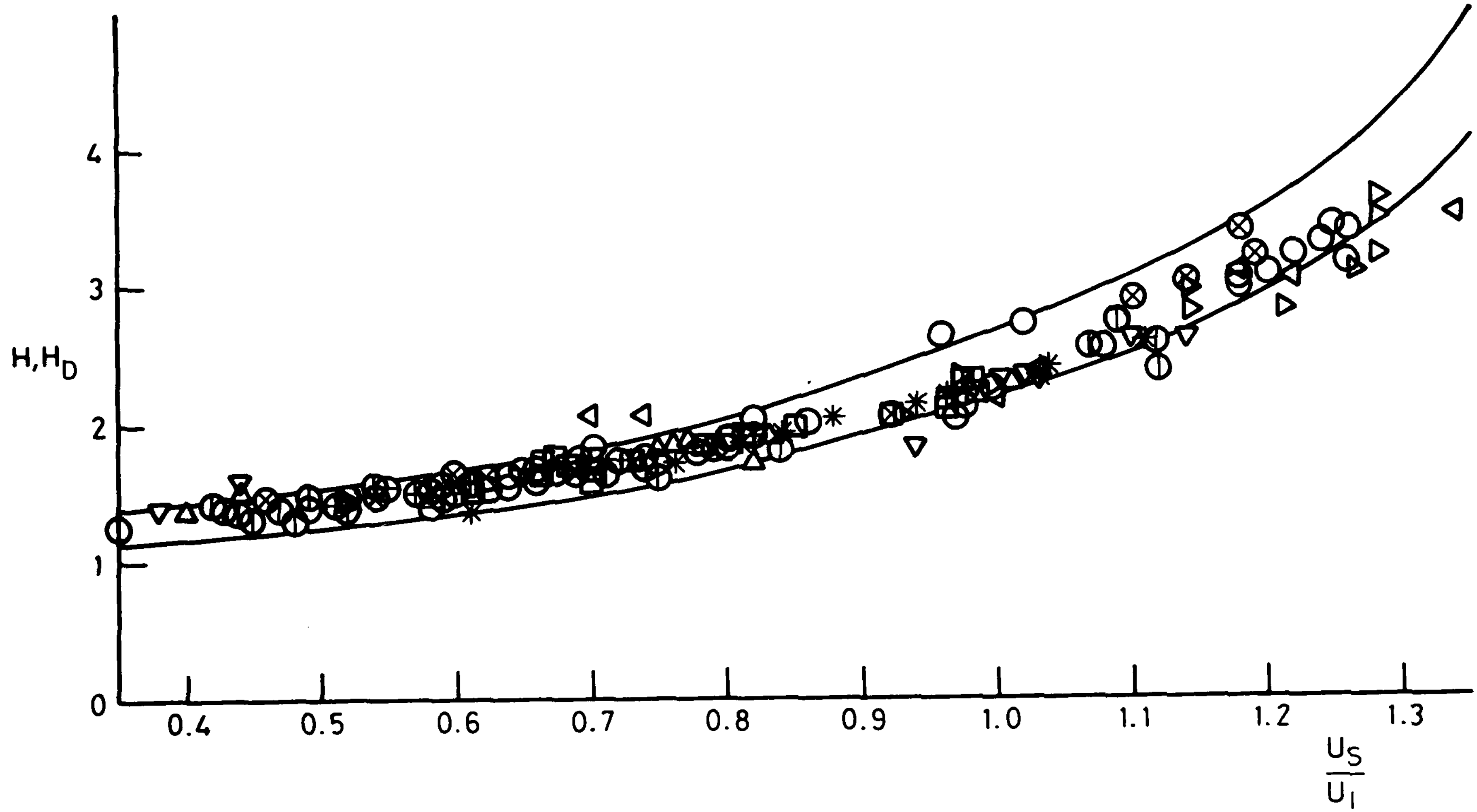


FIG. 20 H,H_D vs U_S/U_I
All data ——— , *equation 9 ± 10%*

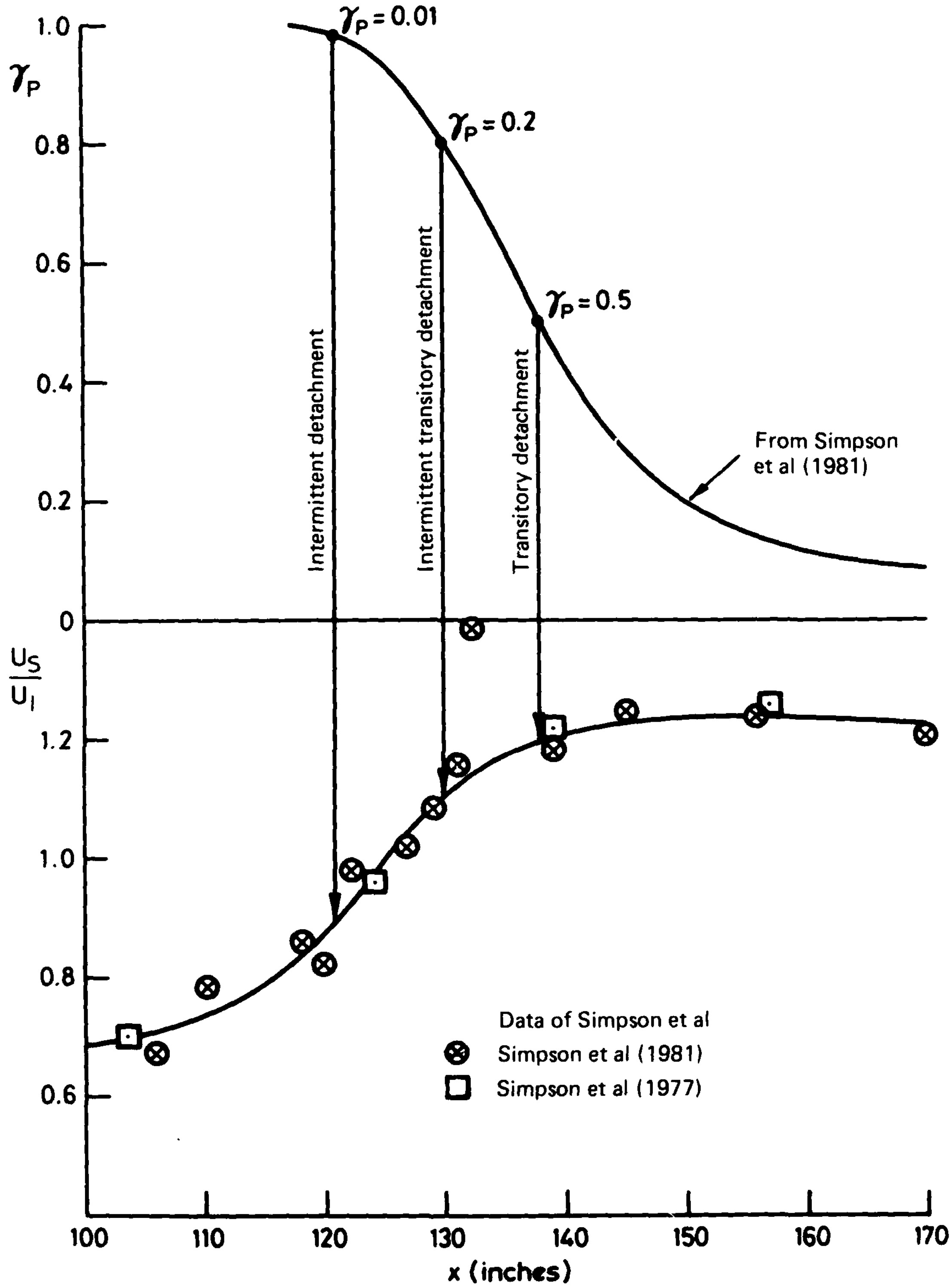


FIG. 21 INTERMITTENT FLOW REVERSAL RELATED TO SIMILARITY VELOCITY RATIO

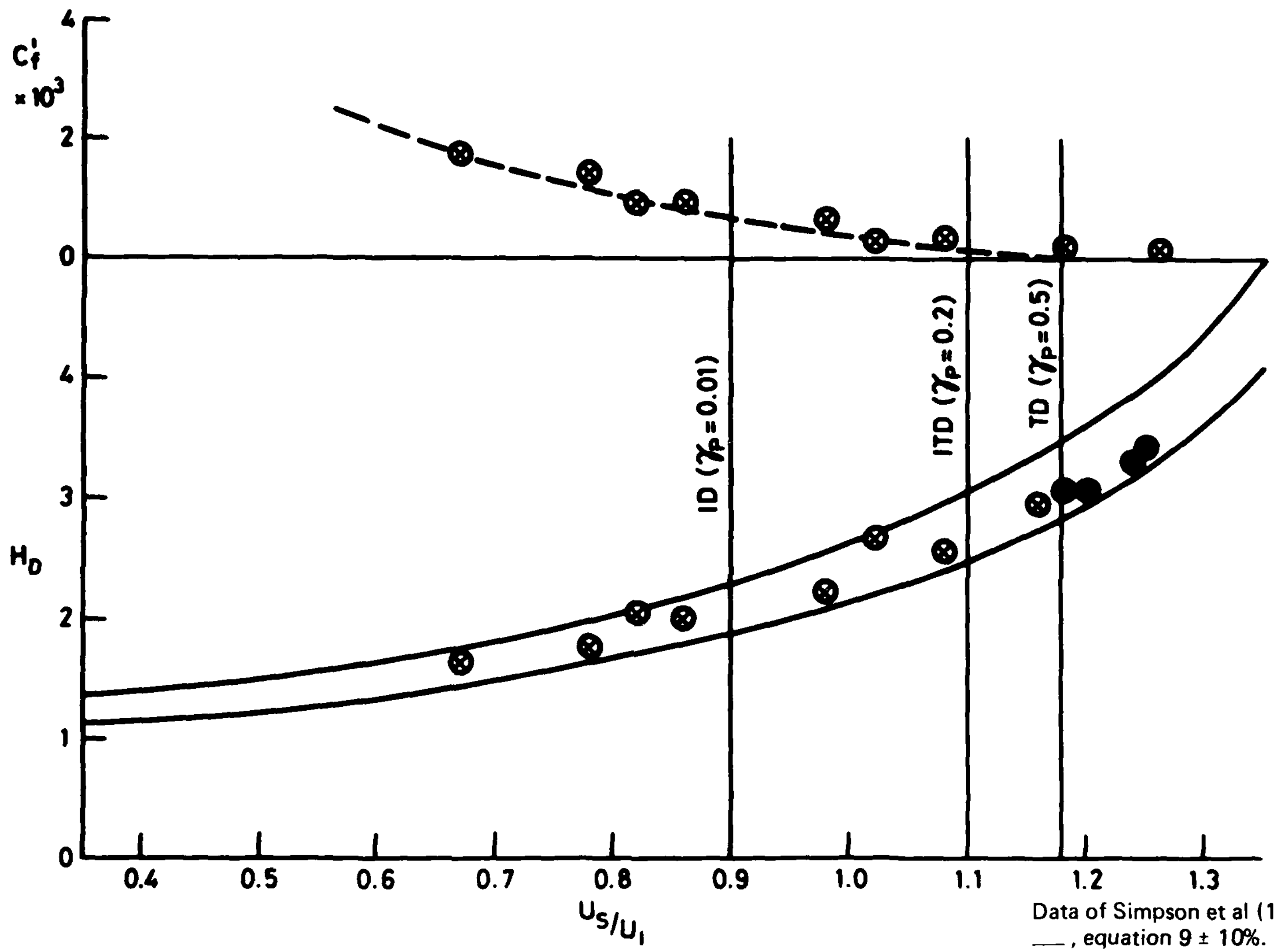


FIG. 22 SEPARATION PARAMETERS – SEPARATING LAYERS

Data of Simpson et al (1981)
___ , equation 9 ± 10%. Solid data points denote data after transitory detachment ($\gamma_p \leqslant 0.5$)

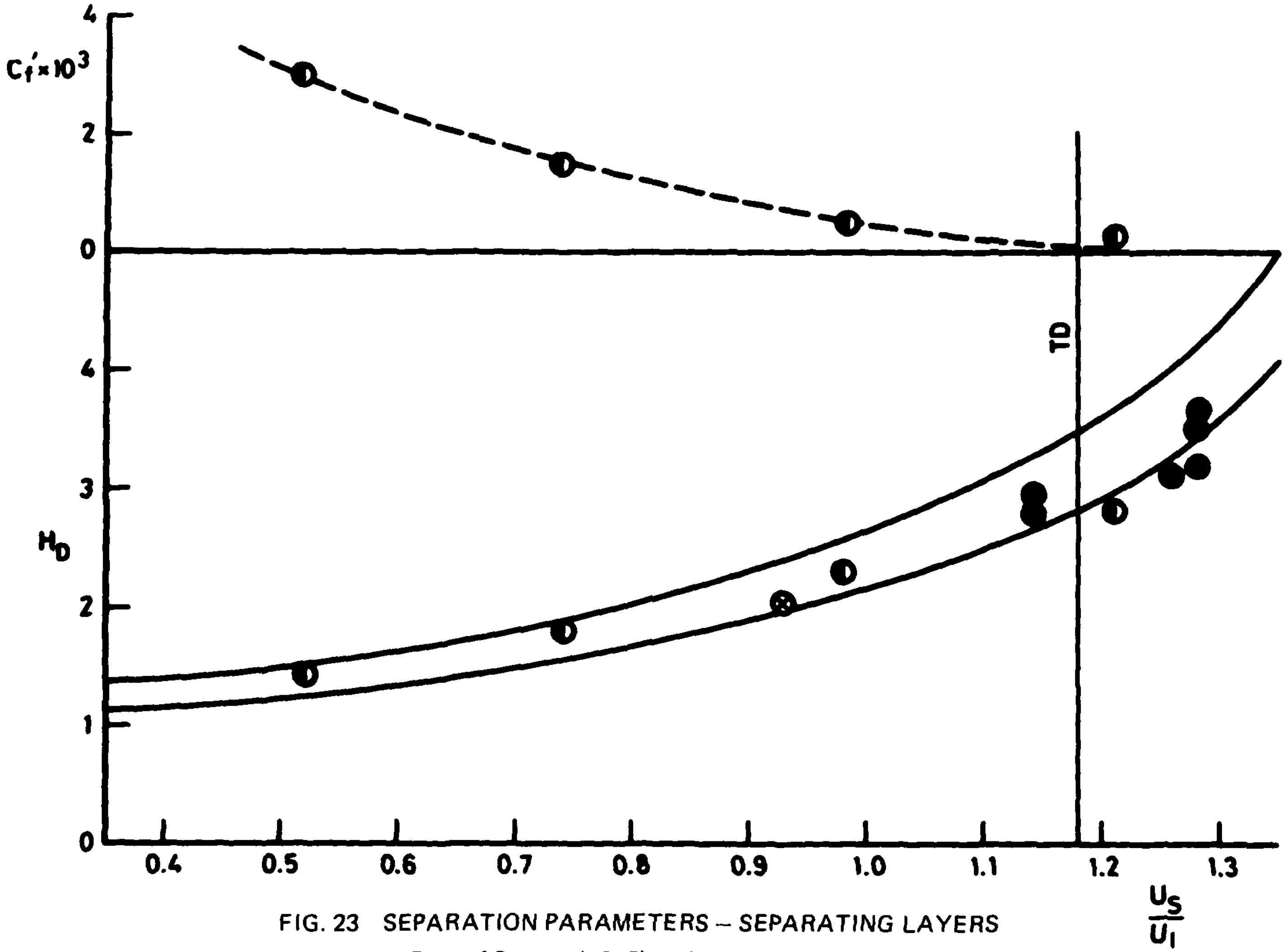


FIG. 23 SEPARATION PARAMETERS – SEPARATING LAYERS

Data of Seddon (1967) basic interaction
——, equation 9 ± 10%; ⊗ – before
detachment, ● – detached flow ($C_f' < 0$),
◐ – reattached flow

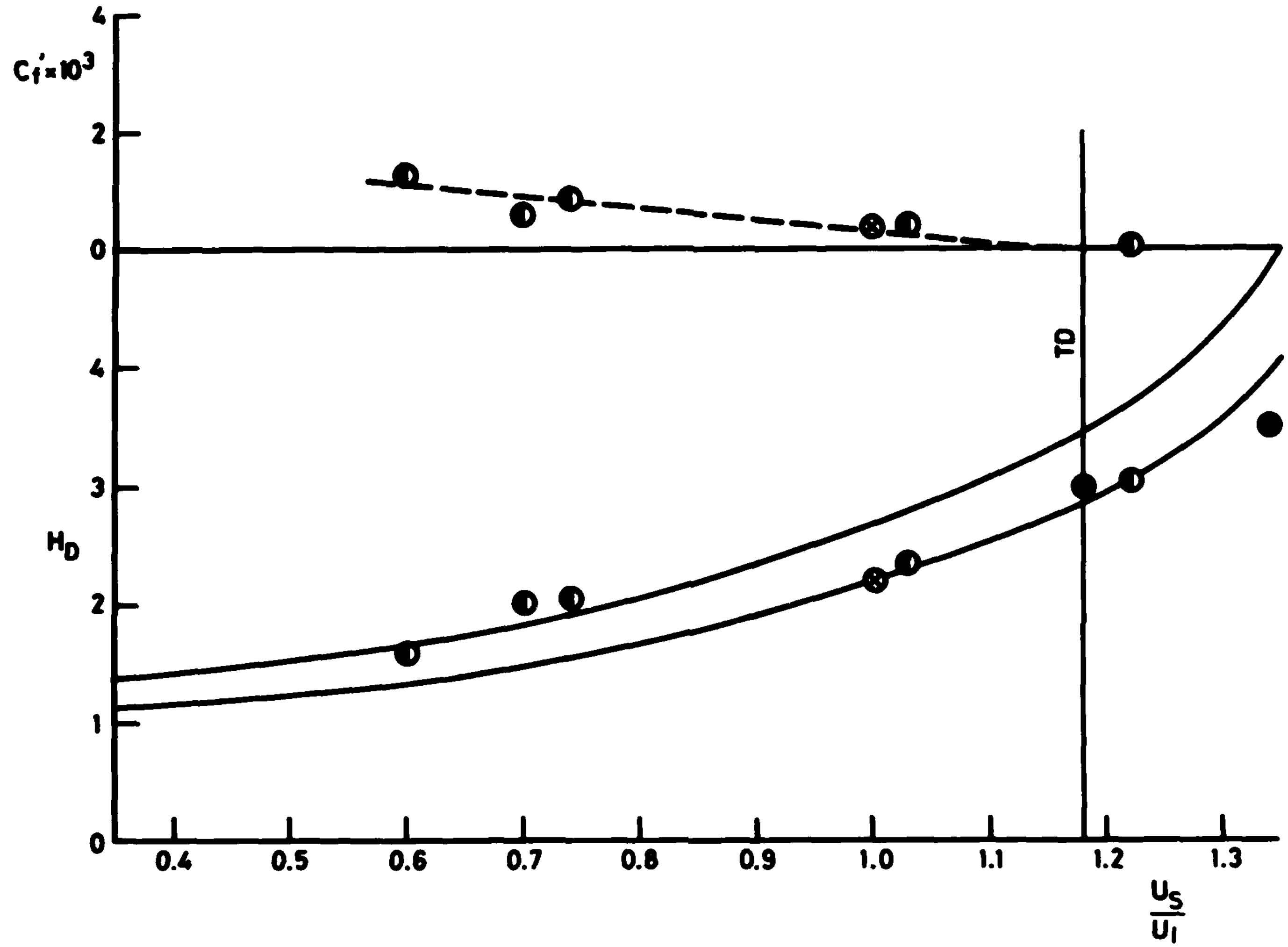


FIG. 24 SEPARATION PARAMETERS – SEPARATING LAYERS

Data of Seddon (1967) modified interaction

——, equation 9 ± 10%; ⊗ – before detachment

● – detached flow ($C_f' < 0$), ◐ reattached flow

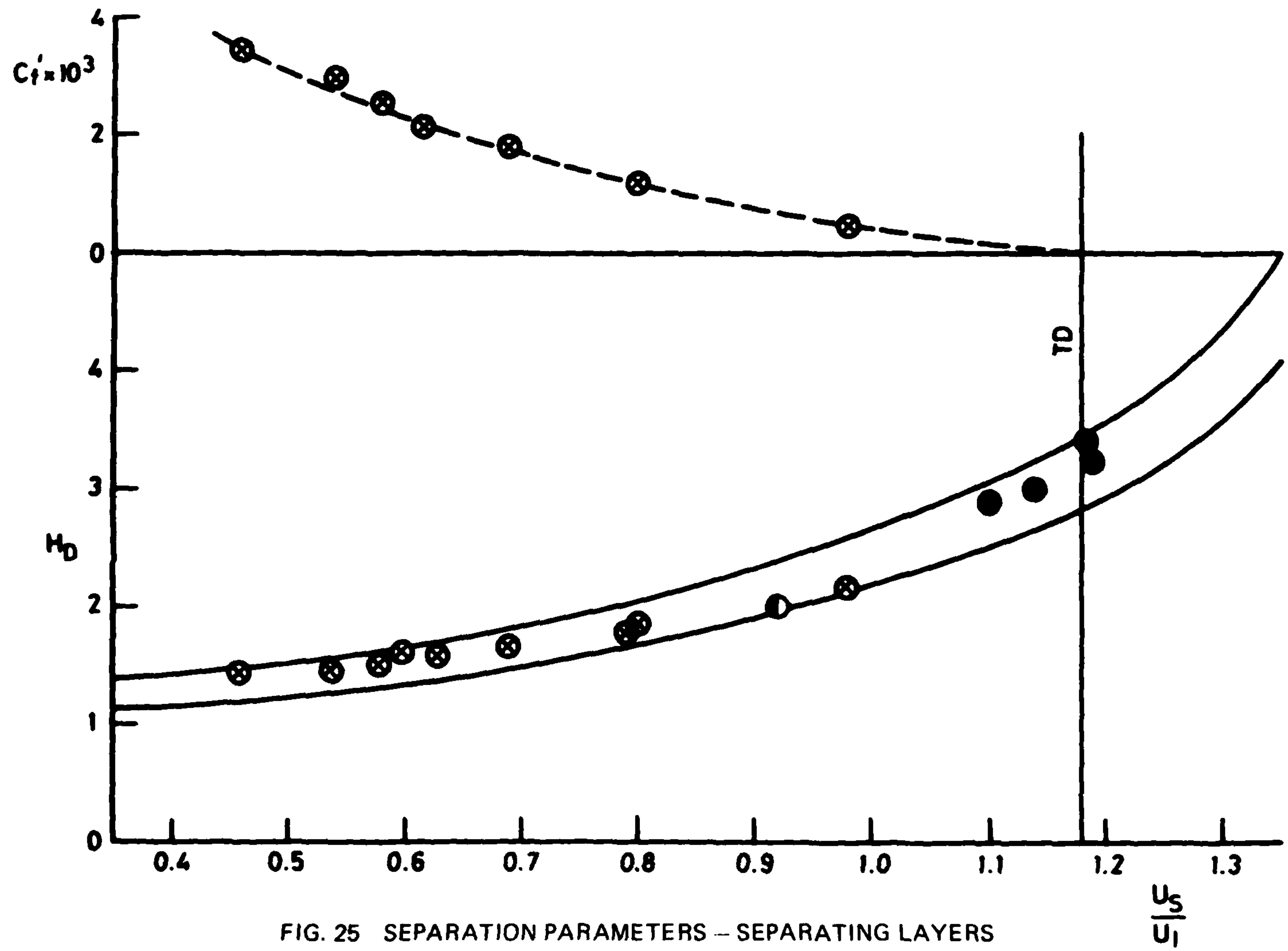


FIG. 25 SEPARATION PARAMETERS – SEPARATING LAYERS

Data of Fairlie (1973) Flow 1

——, equation 9 ± 10%, ⊗ – before detachment

● – detached flow ($C_f' < 0$), ◐ – reattached flow

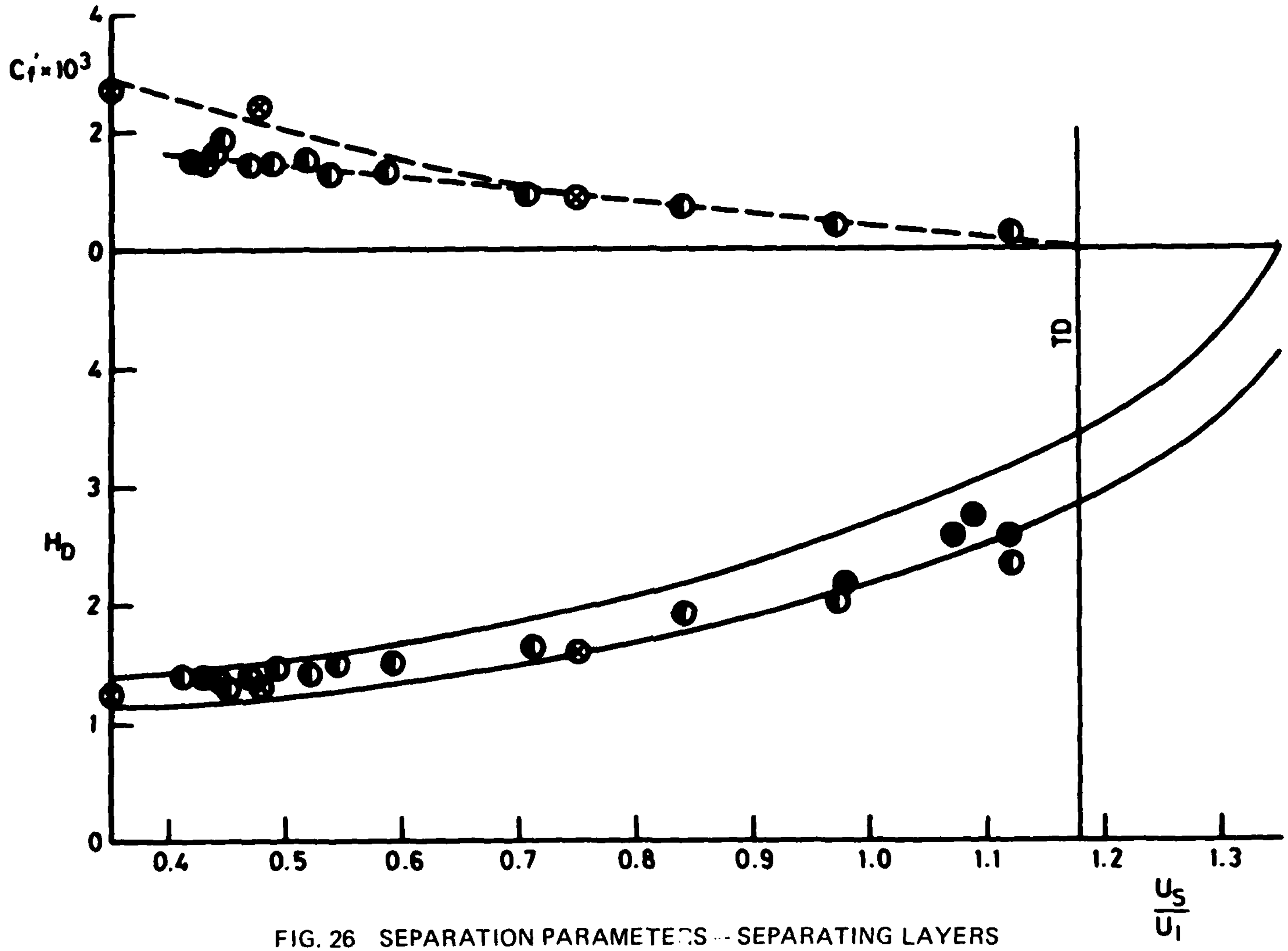


FIG. 26 SEPARATION PARAMETERS – SEPARATING LAYERS
Data of Schofield (1983) Series S
——, equation 9 ± 10%; ⊗ – before detachment,
● – detached flow ($C_f' < 0$), ◐ – reattached flow

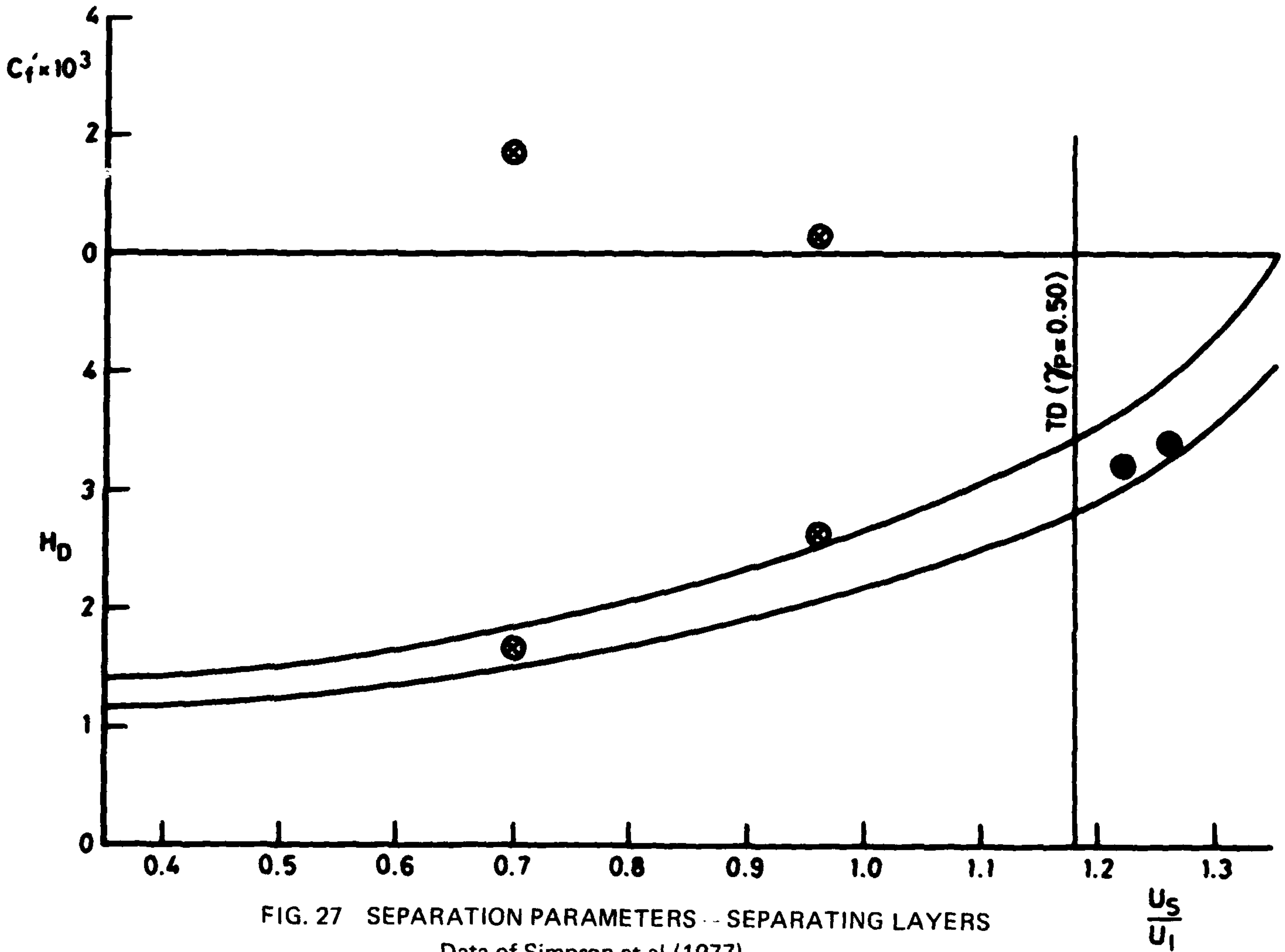


FIG. 27 SEPARATION PARAMETERS -- SEPARATING LAYERS
Data of Simpson et al (1977)
——, equation 9 ± 10%. Solid data points denote data after transitory detachment ($\gamma p < 0.5$)

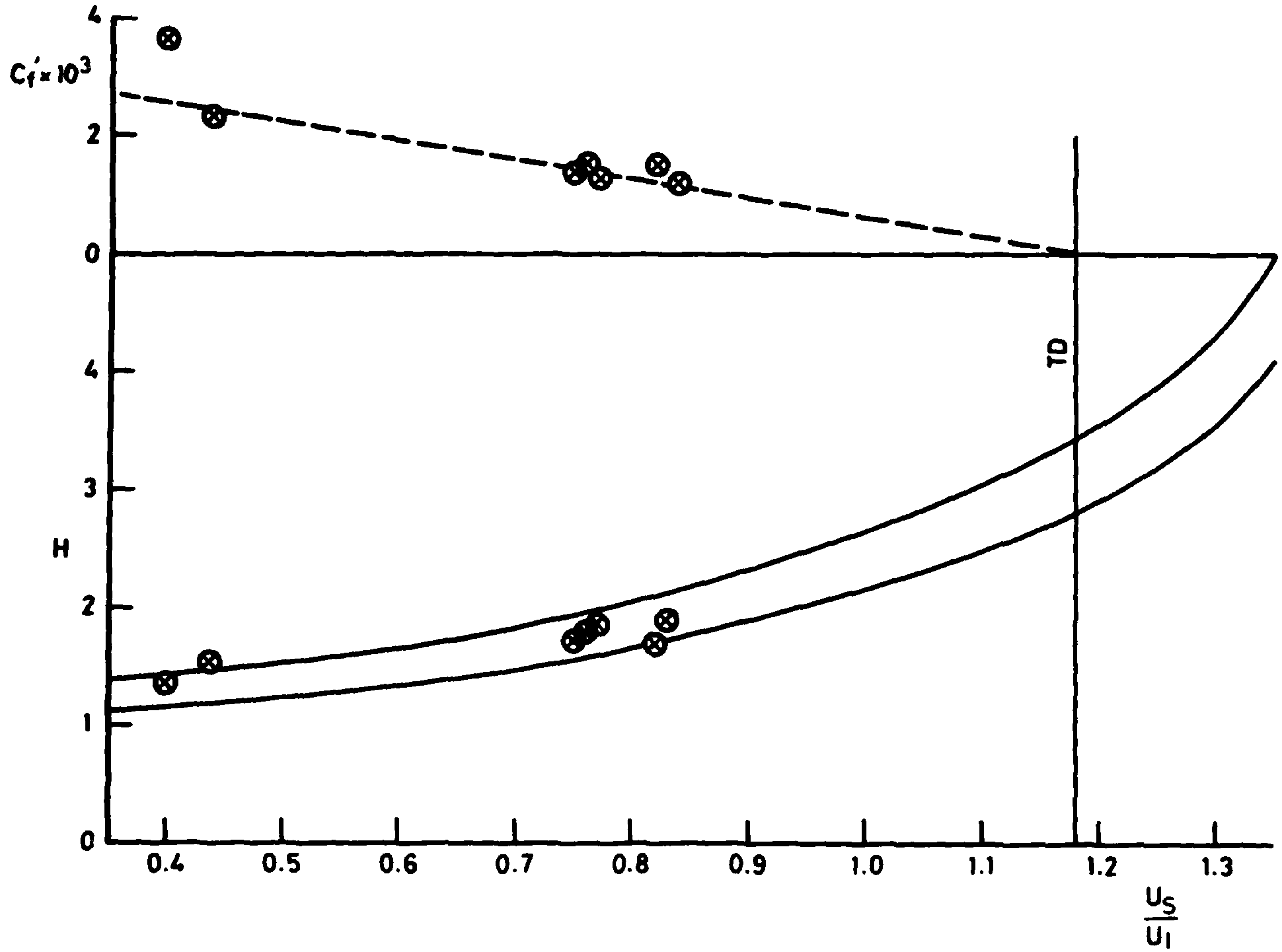


FIG. 28 SEPARATION PARAMETERS - LAYER NEAR DETACHMENT

Data of Stratford (1959) Flow 5

——, equation 9 ± 10%

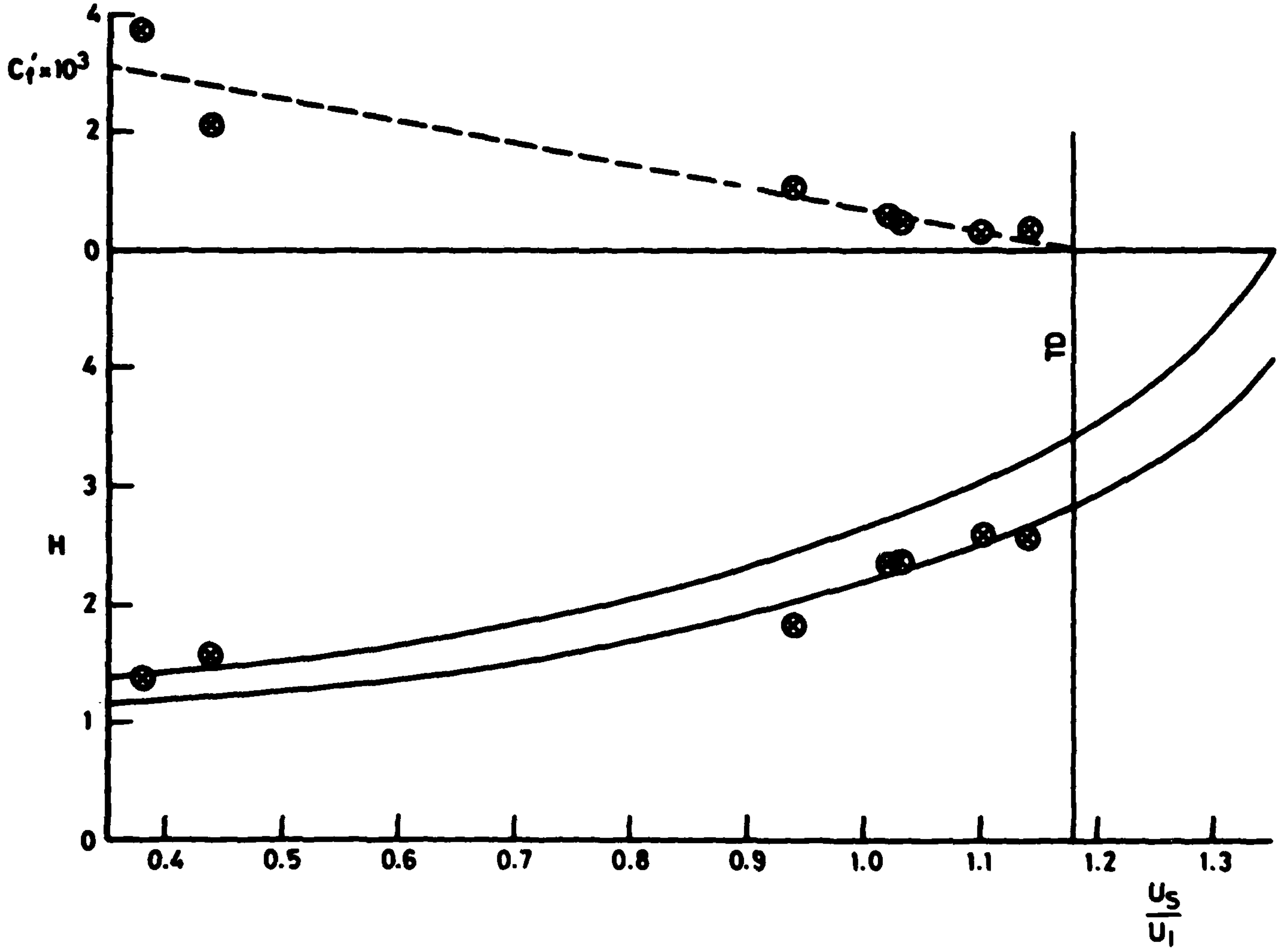


FIG. 29 SEPARATION PARAMETERS -- LAYER NEAR DETACHMENT
Data of Stratford (1959) Flow 6
——, equation 9 ± 10%

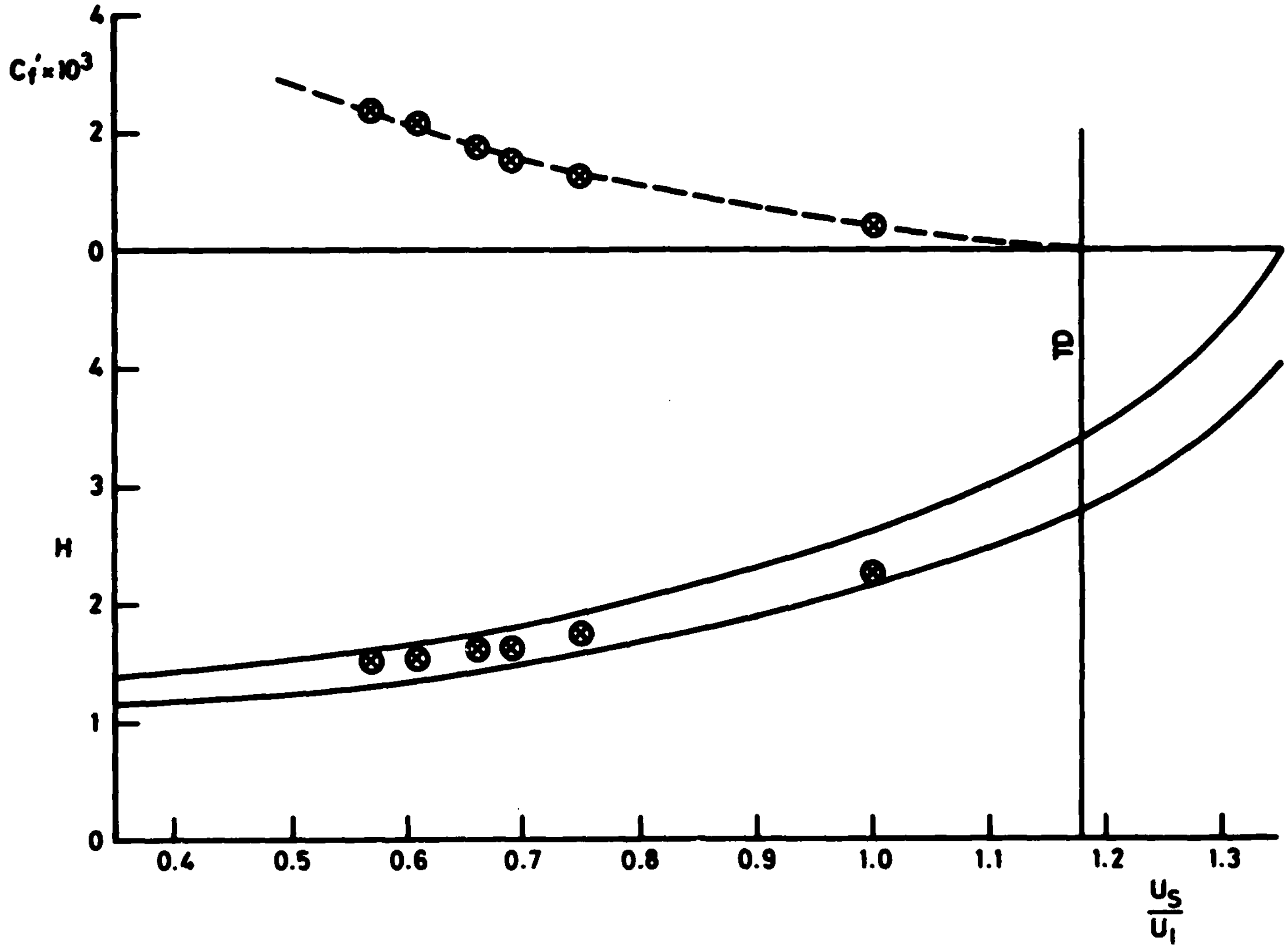


FIG. 30 SEPARATION PARAMETERS – LAYER NEAR DETACHMENT

Data of Fairlie (1973) Flow II

——, *equation* 9 ± 10%

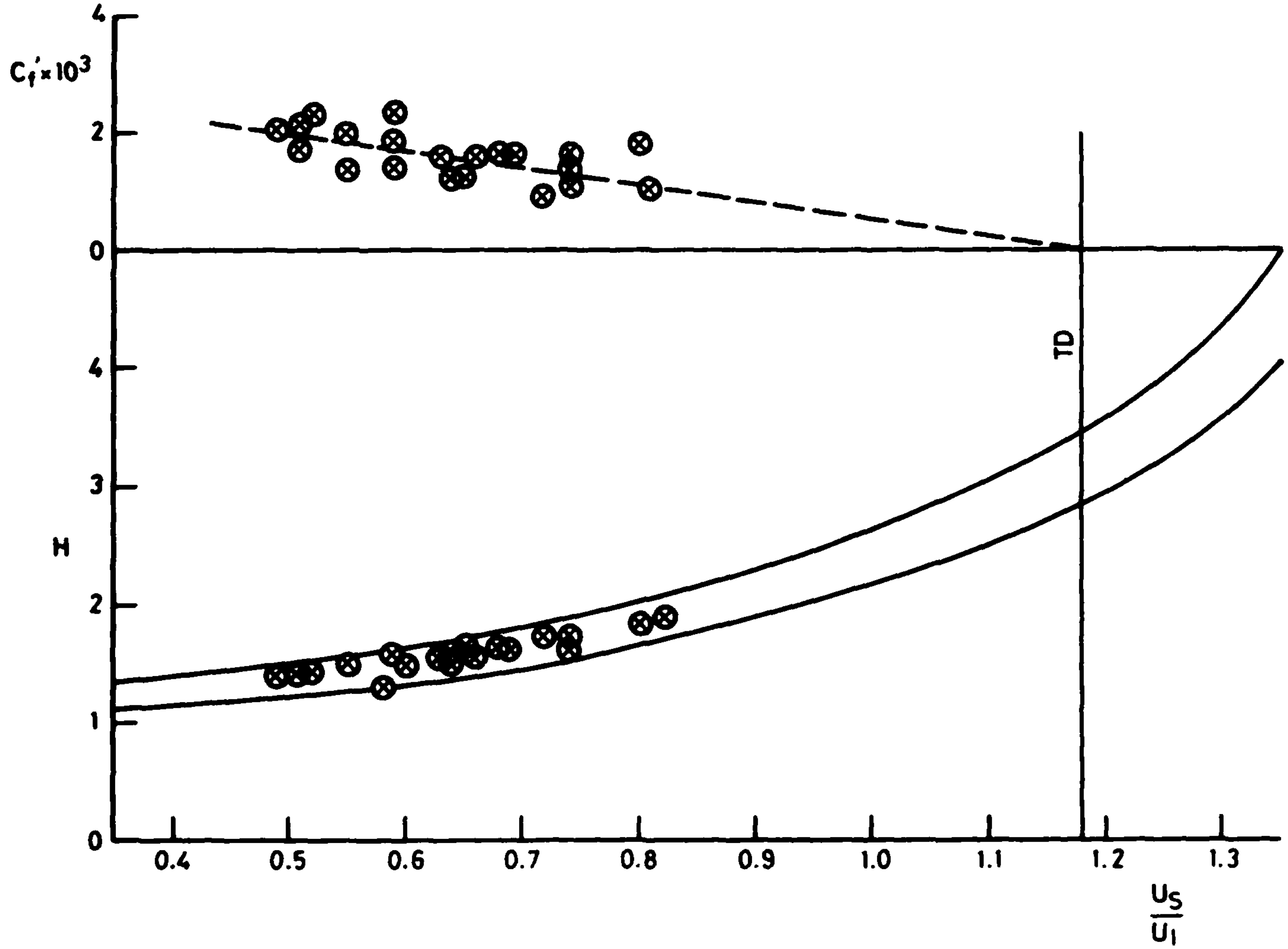


FIG. 31 SEPARATION PARAMETERS · LAYER NEAR DETACHMENT

Data of Schofield (1983) Series L

——, equation 9 ± 10%

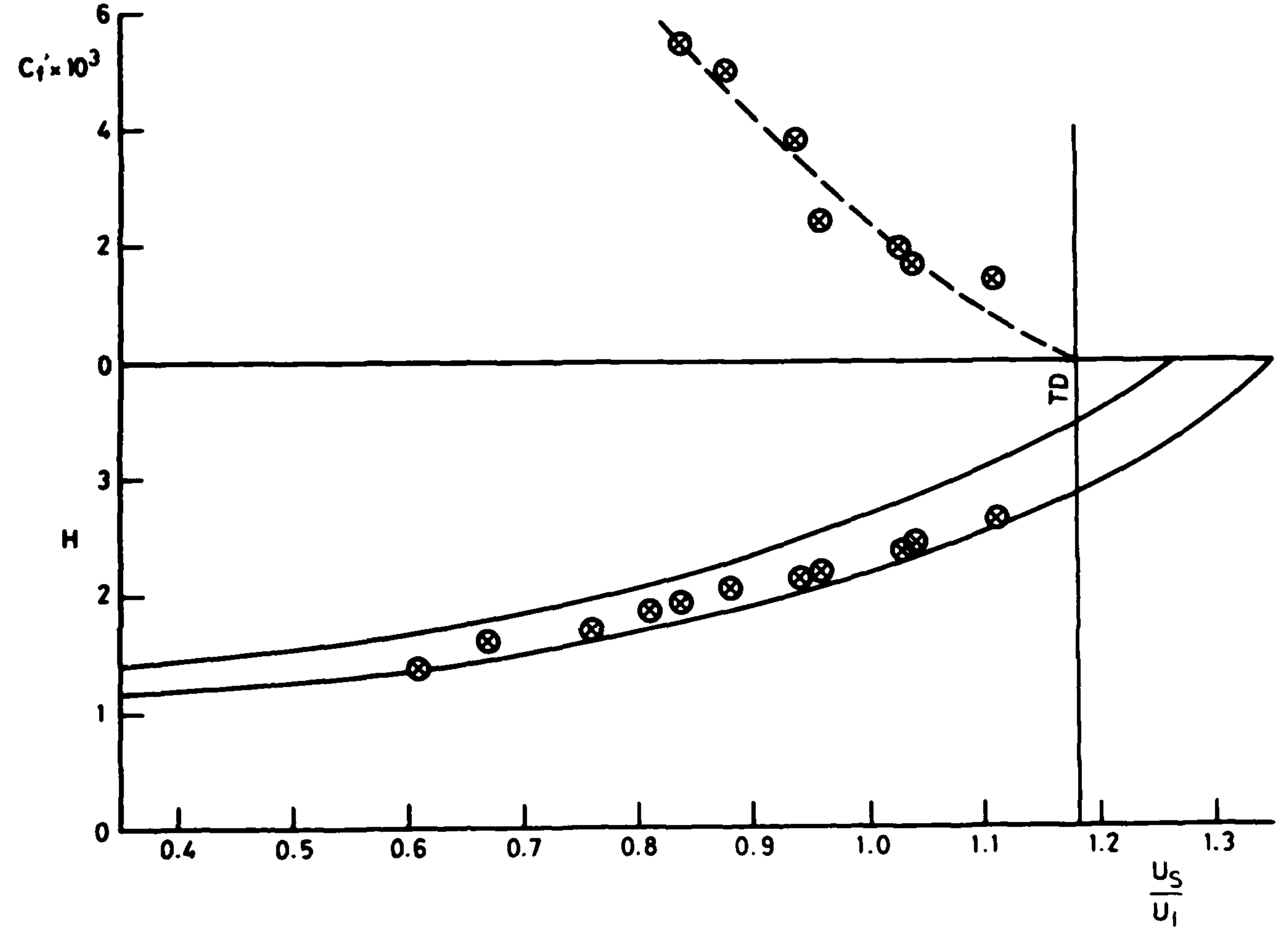


FIG. 32 SEPARATION PARAMETERS – ROUGH WALL LAYER
Rough wall data of Perry, Schofield & Joubert (1969) series k I-I.
——, equation 9 ± 10%

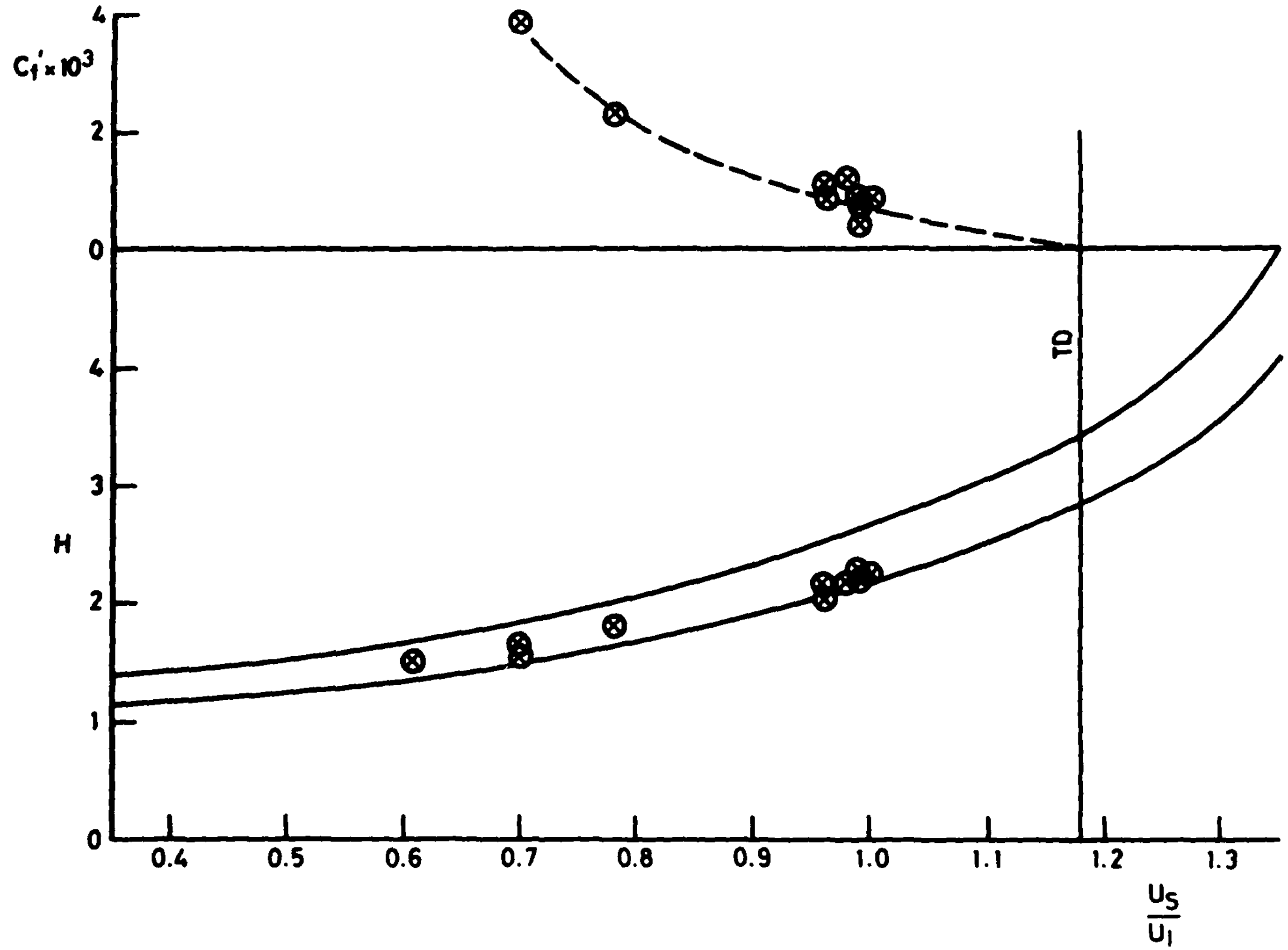


FIG. 33 SEPARATION PARAMETERS – ROUGH WALL LAYER

Rough wall data of Perry et al (1969)
Series DII-II
——, *equation 9 ± 10%*

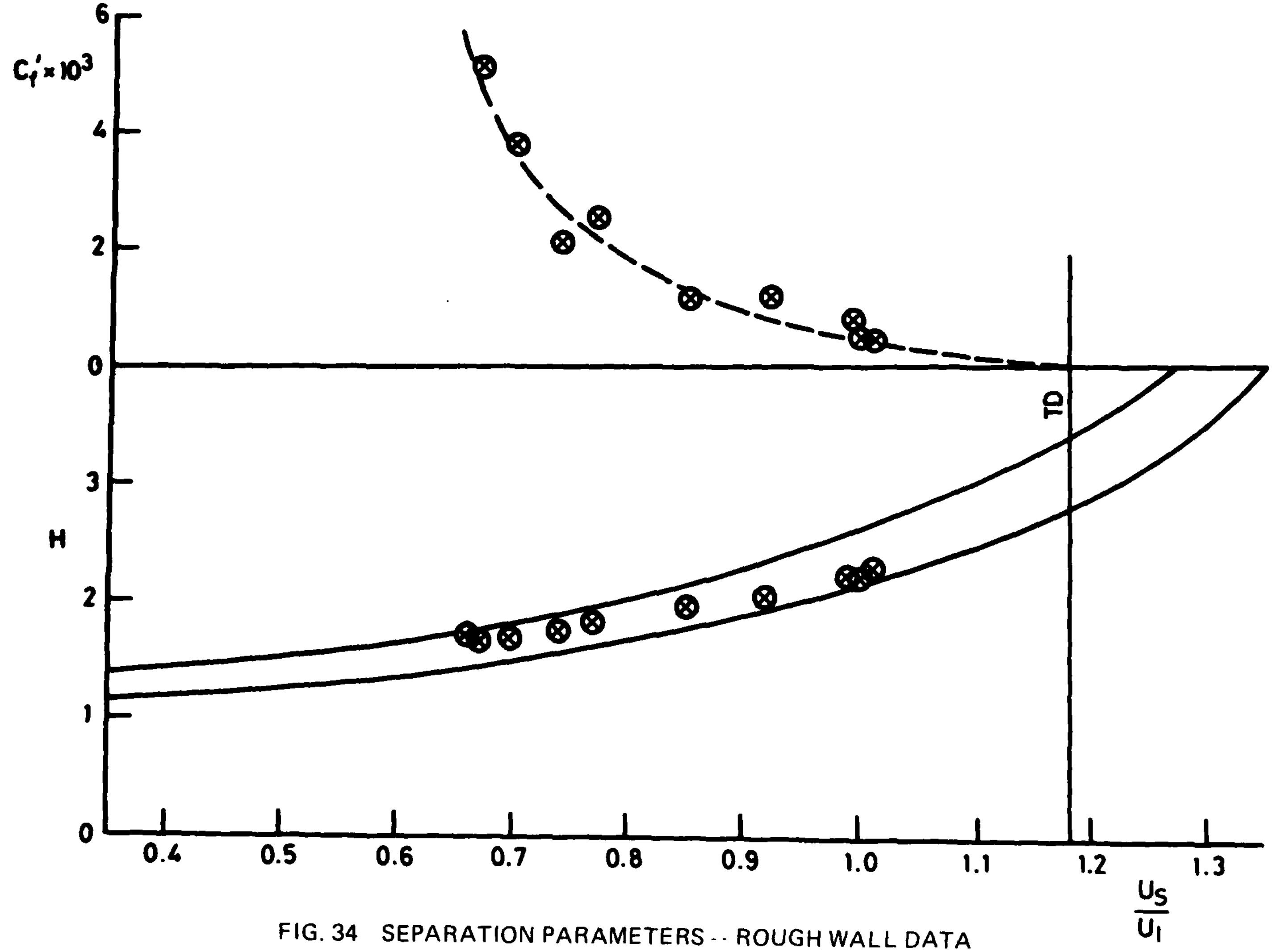


FIG. 34 SEPARATION PARAMETERS -- ROUGH WALL DATA

Rough wall data of Perry et al (1969)
Series DI-I
—, equation 9 ± 10%

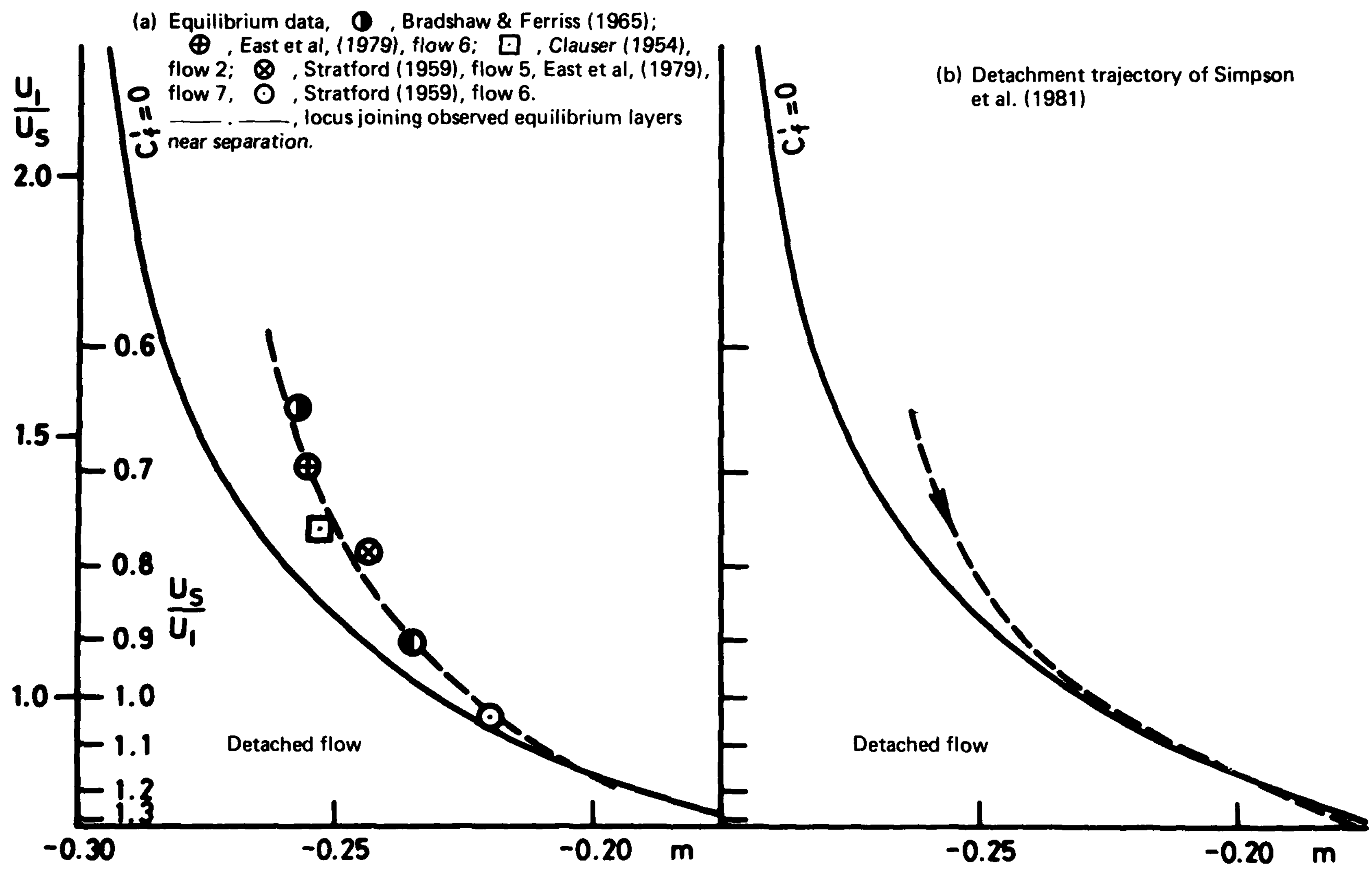


FIG. 35 DETACHMENT TRAJECTORIES

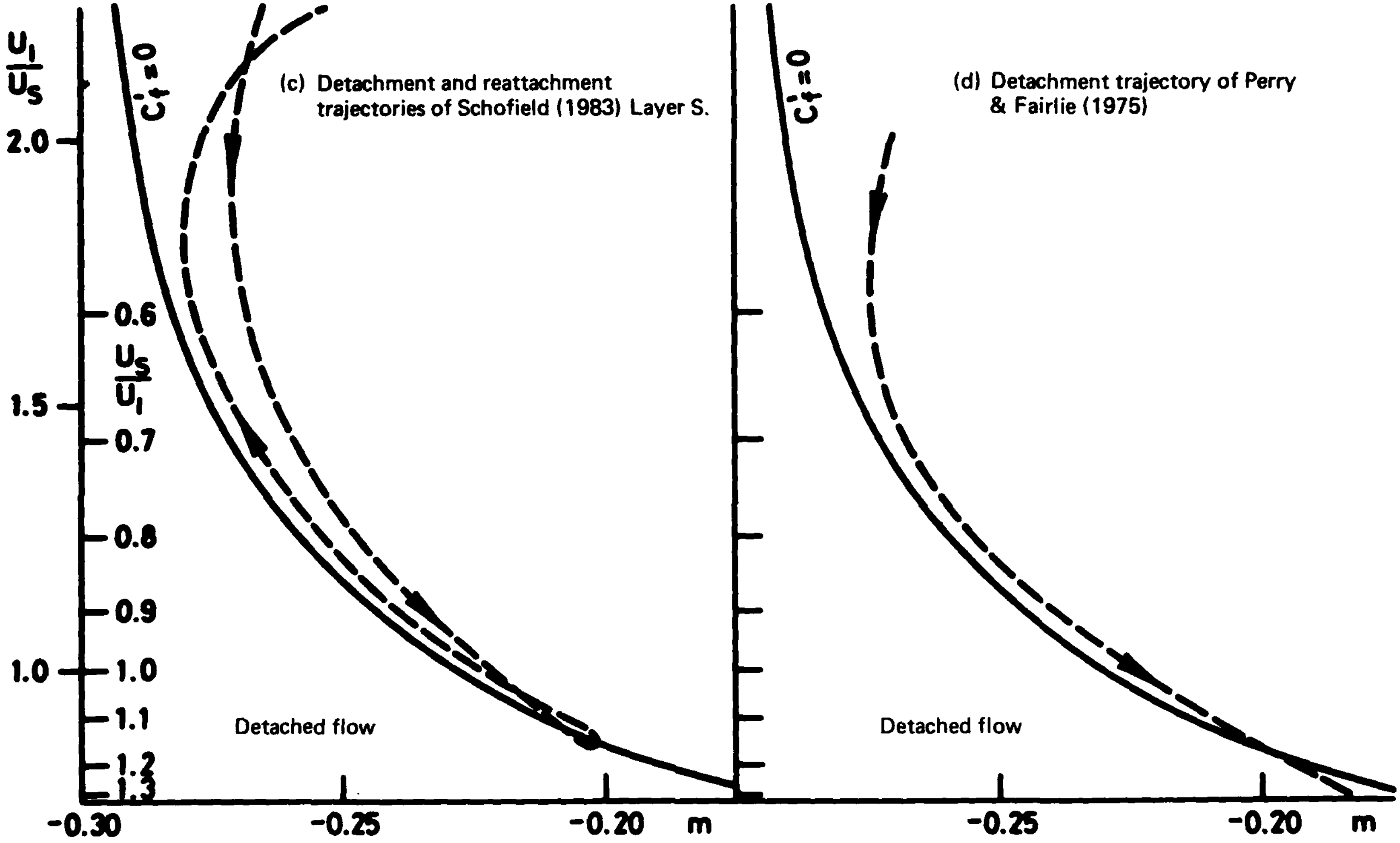


FIG. 35 Continued

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16. Abstract

Some data and theories of two dimensional turbulent boundary layer separation are considered. A description of separating layers based on the Schofield and Perry similarity is proposed. It is shown that the Schofield and Perry defect law can describe detached profiles as accurately as it can describe attached profiles if the origin is shifted, from the wall, out to the zero velocity position in the detached flow. For attached flow the inner wall matching condition is the usual law of the wall. For detached flow the wall matching condition is provided by the reversed flow for which a modified similarity scale is proposed. This extended validity of the Schofield and Perry defect law implies a unique progression of mean velocity profile shapes up to and through separation. Good experimental support for this theoretical result is presented. Experimental evidence also supports the proposition that detachment (and perhaps reattachment) always occurs at the same position on the locus of profile shapes, that is, boundary layers detach with a universal mean

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16. Abstract (Contd)		
profile shape. A comparison of this result with other separation theories leads to another conclusion: that layers which separate in moving equilibrium not only detach with the same mean profile shape, but detach at the same local pressure gradient.		
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